PROCESS SIMULATION OF CO-GASIFICATION SYSTEM USING ADARO COAL & EMPTY FRUIT BUNCHES (EFB) IN ASPEN HYSYS

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Thesis submitted in partial fulfilment of the requirements
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Dedicated to my grandmother & grandfather for nursing me with love and their dedicated partnership for success in my life.

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ABSTRACT

In recent years, alternatives to fossil fuels have been thoroughly discussed and researched. One of the great interests would be co-gasification, which is the process of converting multiple components of carbon-containing feedstock, specifically comprising both biomass and coal in this project, under high temperature with limited air supply in gasifier to produce synthetic gas (syngas). The biggest motivation here is co-gasification is able to utilise coal cleanly while employing biomass as the renewable energy source. Malaysia is one of the biggest producers and exporters of palm oil today, and having Empty Fruit Bunches (EFB) as the palm oil waste. Currently, there is no comprehensive simulation work on co-gasification of using EFB as the main feedstock yet. This has strongly driven the initiation in researching this co-gasification process. ASPEN HYSYS simulator is employed to perform the simulation. Steady state, isothermal model was built in ASPEN HYSYS with the assumptions of all chemical reactions take place at equilibrium state with neglected pressure drop in gasifier. A total of four parameters to be investigated in this simulation consist of temperature, equivalence ratio (ER), feedstock's ratio of biomass to coal (B/C) and ratio of steam to biomass (S/B). A set of total twelve reactor models simulates various reaction zones of the entrained flow gasifier, comprising of pyrolysis of feedstock, combustion and char gasification. The results of simulation are compared with literature work to determine the error. Syngas composition decreases with the increase of ER. The increase of gasification temperature will increase CO and H_2 in the syngas composition, so to increase the heating value of syngas. Increasing S/B will increase the production of CH_4 and H_2 at the expense of CO. For B/C ratio parameter study, the result shows that plain biomass gasification is not efficient as compared to hybrid feedstock – biomass and coal.

ABSTRAK

Penerokaan sumber tenaga alternatif bagi menggantikan bahan api fosil sedang diusahakan melalui penyelidikan di seluruh dunia pada masa kini. Proses "*co-gasification*" merupakan salah satu jalan penyelesaian yang melibatkan penghasilan sumber gas asli daripada karbon. Dalam projek sarjana muda ini, penyelidikan proses gasifikasi dengan menggunakan arang batu dan biojisim bawah suhu tinggi dan bekalan udara yang terhad melalui program simulasi komputer. Proses penjanaan sumber tenaga alternatif secara bersih dan pencemaran udara yang minima telah menjadikan galakan dalam mendalami penyelidikan ini. Malaysia merupakan antara penghasil dan pengeluar bahan kelapa sawit yang utama pada hari ini. Pada masa sama, jumlah sisa kelapa sawit yang besar sesuai dijadikan bahan sumber api alternatif. Setakat ini, tiada penyelidik yang mendalami penyelidikan sebegini. Oleh itu, penyelidikan yang bermakna ini boleh dijalankan. Simulator ASPEN HYSYS telah digunakan dalam menjalankan simulasi proses ko-gasifikasi. Pendekatan tahap suhu proses tetap dan beberapa penganggapan telah digunakan dalam simulasi ini. Terdapat empat parameter yang dikaji dalam penyelidikan ini, iaitu suhu, nisbah biojisim dengan arang batu, nisbah wap dengan biojisim dan nisbah bekalan udara. Sebanyak dua belas reaktor telah digunakan dalam memodelkan pelbagai tahap proses dengan merangkumi pirolisis, pembakaran dan gasifikasi. Keputusan simulasi menunjukkan bahawa penghasilan sumber gas asli menurun dengan peningkatan nisbah bekalan udara. Peningkatan suhu proses "*co-gasification*" akan meningkatkan penghasilan gas karbon monosida dan hidrogen. Peningkatan nisbah wap dengan biojisim akan meningkatkan penghasilan gas metana dan hidrogen, tetapi komposisi CO akan menurun. Bagi kajian nisbah biojisim/arang batu, simulasi menunjukkan bahawa gasifikasi hibrid menggunakan arang batu dengan biojisim adalah lebih efisien berbanding dengan gasifikasi biojisim.

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NOMENCLATURE

A	Pre-Exponential Factor
C	Concentration of Chemical Substance
E_a	Activation Energy
G	Gibbs Free Energy, J/mol
k	Rate Coefficient / Rate Constant
R	Universal Gas Constant
r	Rate of Reaction
T	Thermodynamic Temperature in Kelvin
ΔH_R	Heat of Reaction

Greek Letters

ρ	Density

Subscripts

i	species
a	Chemical A
b	Chemical B

Superscripts

*	Modified Value
o	Thermodynamic Standard State

LIST OF ABBREVIATIONS

B/C	Biomass-to-Coal Ratio
BFB	Bubbling Fluidised Bed
CE	Carbon Gasification Efficiency
CFB	Circulating Fluidised Bed
CGE	Cold Gas Efficiency
CHP	Combined Heat and Power
CPO	Crude Palm Oil
DAF	Dry Ash-Free
DFBG	Dual-Fluidised Bed Gasifier
EFB	Empty Fruit Bunches
EIA	Energy Information Administration
Eqn.	Equation
EF	Entrained Flow
EFG	Entrained Flow Gasification
ER	Equivalence Ratio
FAO	Food and Agriculture Organization of the United Nations
FC	Fixed Carbon
GHG	Greenhouse Gases
GSTC	Gasification & Syngas Technologies Council
GU	Gasification Unit
HHV	Higher Heating Value
IEA	International Energy Agency
kWh	Kilowatt-hours
LHV	Lower Heating Value
MC	Moisture Content
MPOB	Malaysian Palm Oil Board
NETL	National Energy Technology Laboratory
PA	Proximate Analysis
PE	Polyethylene
PR	Peng-Robinson
S/B	Steam-to-Biomass Ratio
SNG	Synthetic Natural Gas

Stoich	Stoichiometry
Syngas	Synthetic Gas
TWh	Terawatt-hours
UA	Ultimate Analysis
VM	Volatile Matter
WGS	Water-Gas Shift

CHAPTER 1

INTRODUCTION

1.1 Motivation and Problem Statement

The demand for energy is increasing annually in the world as it is a necessary input to sustain living. As a result, obtained from the generalization of agricultural, domestic and industrial activities, the demand for energy has grown dramatically, especially in emergent countries (Baños et al., 2011). International Energy Agency (IEA) had estimated that the global energy consumption in 2012 was 5.6×10^{20} joules. In 1973, the final energy consumption in the world had been reported 54335 terawatt-hours (TWh) meanwhile the figure had rocketed to 104426 TWh in 2012 (IEA, 2014). It can be seen that the global energy consumption had almost been doubled up within 39 years. With the rapid development and modernisation in Malaysia, U.S. Energy Information Administration (EIA) had reported that 120 billion kWh of energy, in the context of electricity, was utilised in 2012, which had a double increase since 2000 (EIA MEIH, 2014). The statistical analysis has strongly proven that the demands for energy globally and locally have swiftly increased and have been projected to grow by 56% between 2010 and 2040 (IEO, 2013).

Currently, Malaysia is having heavy reliance on non-renewable fossil fuels in generating energy. In 2012, Malaysia’s primary energy consumption was majorly contributed by petroleum and natural gas, with estimated shares of 40% and 36% respectively (IEA, 2014). According to the forecasts of fossil fuels reserves in Malaysia, petroleum is estimated to be depleted by 2020, followed by natural gas by 2058 and coal around the year 2066 (Muda & Tey, 2012). As the fossil fuels depletion worrisome is increasing with years, the demand for effective and efficient alternative energy technology, which must be sustainably renewable, is urgent in recent time. The urge of using renewable energy such as solar power, hydro power, wind, biomass, etc. is driven to replenish the exhaustion of fossil fuels. However, alternative energy comes out with various important drawbacks, such as the discontinuity of generation, as most renewable energy resources depend on the climate, which is why their use claims complex design, planning and control optimization methods (Baños et al., 2011). Despite the obvious advantage of its renewable content, there is still a certain gap in exploiting alternative energy efficiently.

Owing to that, there has been interest in the utilisation of biomass for production of environmental friendly biofuels (Mohammed et al, 2011). Biomass refers to products, by-products, residues and waste from forestry, agriculture and related industries, which also includes the non-fossilized and biodegradable organic fractions of industrial and municipal solid wastes (Demirbas, 2011). In Malaysia, the production of palm oil in 2015 was almost 20 million tonnes (MPOB, 2015). The massive production of palm oil and its products has promoted Malaysia to be one of the largest producers and exporters of palm oil products in international market. With the exceptionally large production of palm oil has given the advantage of having huge amount of empty fruit bunches (EFB) too, which is the by-product from crude palm oil mill. A total of 79.3 million tonnes of fresh fruit bunches is processed in 2006 and 17.4 million tonnes of EFB have been generated (Amal, 2008). EFB is categorised as biomass element, which would benefit Malaysia’s vision in adopting alternative energy, as biomass is recognised as clean and environmentally friendly fuel source, since the International Energy Agency 2002 reported that most of the emissions come from energy (80%) and agriculture 20%. Biomass can be utilised as an energy resource which can be efficiently achieved by thermo-chemical conversion technology: pyrolysis, gasification or combustion (Mohammed et al., 2011).

Coal gasification has reached its maturity at the moment. In recent years, due to the continuing increase in oil prices, production of liquid fuel from coal has already shown the potential of economical competitive advantage. This is especially true for the low rank coal which is not suitable for direct combustion and coking; producing liquid fuel from these types of coals could be a more viable option (Xu, 2013). However, the utilization of coal creates an environmental issue because of its generation of CO_2 and emission of pollutant substances such as SOx. Hence, alternative feed such as biomass is taken into consideration to replace coal.

However, in fact, it is practically impossible at the moment to completely replace coal with biomass resources because of the low energy value of biomass (Mabizela, 2014). Hence, co-gasification process technology has been a significant research in employing biomass EFB and coal as feedstock to produce clean gas effectively. Co-gasification of coal and biomass has some synergy (Sjöström, 1999). synergistic relationship when used together. The synergistic relationship between coal and biomass is defined as when two or more causes combine together to produce a result that is greater than the sum of its parts. If an amount of coal produces syngas with a certain heating value, and an amount of biomass produces syngas with a different heating value, to say that the two are in synergism with regards to syngas production means that the heating value reached by the combination of both amounts is greater than it would have been if they were gasified apart and both streams of syngas are collected together afterwards (Long & Wang, 2011). This process technology is able to solve the issue of EFB as the waste from the crude palm oil production, meanwhile it can contribute in generating alternative energy.

Co-gasification is an established technology (Ishi, 1982). It refers to the process of converting multiple components of carbon-containing feedstock, comprising both biomass and coal here, under high temperature and high pressure using limited oxygen in gasifier to produce synthetic gas which is to be utilised for other processes such as methanol production, as energy, etc. with the advantage of minimal environmental footprint. There is an apparent knowledge gap in this co-gasification technology using EFB as biomass element and little relevant literature was found. The variant of feedstock ratio of EFB to coal, temperature, the steam to EFB ratio and pressure will be the components to be solved in order to obtain the producer gas in desired range to feed the demand of end users.

Environmentally, biomass is sustainable and hugely carbon neutral as the plants absorb CO_2 during their growth, and thus utilising biomass for energy will be able to reduce the environmental footprint compared to using pure coal (Collot et al. 1999). The problem of environment and economic growth with using co-gasification will be investigated throughout the research in the process simulation of co-gasification system.

1.2 Objectives

The objectives of this research have been comprised as following.

1) To develop the process simulation of co-gasification system using biomass (raw EFB) and coal (Adaro Coal) as the feedstock.
2) To investigate the effect of manipulated variables, consisting of equivalence ratio (ER) temperature, steam-to-biomass (S/B) ratio, biomass-to-coal (B/C) ratio in co-gasifier on the composition of producer gas.

1.3 Scope of Research

The scope of this research has been emphasised as below.

1) Main manipulated variable to be studied is the effect of temperature on composition of producer gas.
2) Equivalence ratio (ER) of air flowrate is studied to determine its effect on syngas composition.
3) Ratio of biomass-to-coal (B/C), with B0 is 0% biomass and B100 is 100% biomass, in co-gasification system and steam to biomass ratio (S/B) in composition of produced syngas is studied and analysed.
4) The conversion of feedstock to char, possibility of tar to be reduced, CO, H_2 and CO_2 composition with EFB/coal ratio are simulated using ASPEN HYSYS.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This research paper presents the process simulation of co-gasification system. The process simulation software employed here is ASPEN HYSYS. The world is facing serious carbon environmental footprint issue, especially greenhouse effect which is due to the heavy concentration of CO_2 gas caused by burning of the fossil fuels (Hannah, 1997). Fossil fuels refer to oil, coal, gas and also the cutting and burning of the world's forests on a massive scale (Hannah, 1997). As a consequence, the utilisation of renewable energy has been emphasised on due to the world environmental concerns, rocketing demand for energy and also the steady progress in renewable energy technologies (Parida et al., 2011). One of the arising alternative energy is the use of biomass. There are several ways to convert the raw biomass into valuable energy, which are combustion, co-combustion with coal, pyrolysis and gasification (Chmielniak & Sciazko, 2003). Among the thermochemical conversion methods, gasification of using biomass as feedstock has drawn full attention from researchers for its ability to produce synthesis gas (syngas), which mainly consists of CO and H_2 which offers the opportunity to supply a broad range of environmentally clean fuels and chemicals (Wender, 1996). Gasification of biomass is convincingly efficient to be physically and chemically upgraded to products with greater value, for instance methanol or gasoline, as it contains CO, CO_2, H_2, CH_4 and significant quantities of both saturated and unsaturated hydrocarbons (Bridgewater & Grassi, 1991). Gasification has acted the major part in industrial growth since 1812 when the gasification has become a commercial process with the foundation of the London Gas, Light and Coke Company (Higman & Burgt, 2003). According to Gasification & Syngas Technologies Council (GSTC), there is only one gasification plant located at Bintulu, Sarawak Malaysia which using Shell Gasification Process as its operation technology. There is no upcoming gasification project in Malaysia, according to National Energy Technology Laboratory (NETL) in 2016. However, the sole gasification on biomass will not give satisfactory result of energy. The main biomass feedstock to be studied thoroughly in this paper will be empty fruit bunches (EFB), which is a by-product from the process of crude palm oil. Furthermore, co-gasification of biomass and coal can be considered as a potential fuel-base for gasification and further syngas production to be utilised in power generation (Chmielniak, 2003). This research paper will be emphasised on the process simulation of co-gasification of biomass and coal.

2.2 Application of Gasification

Gasification adds value to low- or negative-value feed stocks, such as biomass, by converting them to marketable fuels and products (Ronald, 2010). Figure 2-1 has demonstrated the syngas market in 2005, where we can see that most of the syngas is utilised on ammonia production.

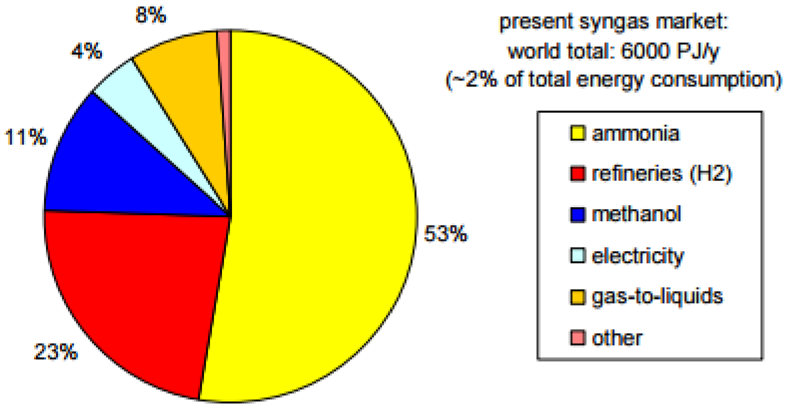

Figure 2-1: Syngas market (Boerrigter & Rauch, 2005).

Undoubtedly, gasification is the most dominant technology in producing syngas, as the producer gas serves as the intermediates in the high-efficient power production or the synthesis from chemicals and fuels (Boerrigter & Rauch, 2005). Basically, the application of producer gas from gasification can be categorised into few major fields which are power generation, Synthetic Natural Gas (SNG), transportation fuels and also chemical synthesis. The common applications and current application of syngas have been demonstrated in Table 2-1.

Table 2-1: General application of gasification products (Boerrigter & Rauch, 2005).

Application	**Description**
Power Generation	**Co-firing** Inject producer gas in the combustion zone of coal boiler for the co-firing in existing coal power plants. **Combined heat and power (CHP)** The product gas is fired on a gas engine in CHP after removing tar, where the scale of plant will be limited by the local heat demand. Integrated gasification combined cycle (IGCC) Producer gas can be used in electricity production on larger scales, where the gas is fired on a gas turbine the gasification will be carried out at the pressure of turbine as it requires a pressurised feed gas the biomass gasification. **Fuel Cells** This application for the production of electricity is still in its early development, where it has the theory that higher electrical efficiencies could be achieved compared to simple combustion system and gas engines.
Transportation Fuel	**Fischer-Tropsch (FT) Synthesis** In FT synthesis, one mole of CO reacts with two moles of H_2 to form mainly paraffin straight-chain hydrocarbons (C_xH_{2x}) with minor amounts of branched and unsaturated hydrocarbons and primary alcohols. This process can be used to produce either a light synthetic crude oil (syncrude) and light olefins or heavy waxy hydrocarbons.
Transportation Fuel	**Methanol** It can be produce by means of the catalytic reaction of CO and some CO_2 with H_2 which have been obtained from gasification. The presence of a certain amount of CO_2 in the percentage range is vital

Application	Description
	for the reaction's optimisation. These processes are classified according to high, medium and low pressure.
Chemical Synthesis	**Ammonia synthesis for fertiliser production** In syngas-based process, the ammonia synthesis illustrates two obvious characteristics. Firstly, a high concentration of the inert gas nitrogen is acceptable and even required. Secondly, the specifications for oxygen-containing gases, particularly pointing at CO_2 and CO gases that typically are present in syngas are very strict in order to optimise the process of ammonia.
	Hydroformylation of olefins The reaction of olefins with syngas (CO and H_2) from gasification in the presence of homogeneous catalysts will form aldehydes which contain an additional C atom. This hydroformylation, also called oxo-synthesis or Roelen reaction, is a commercial-scale process for the production of aldehydes.
	Hydrogen in refineries Gasification produces syngas which is one of the main sources for H_2 used in refineries. In refineries, H_2 gas is used for the hydro-treating which used to remove impurities, and hydro-processing operations that is employed to upgrade the heavy oil fractions to lighter products which will be used in the production of transportation fuels.
Chemical Synthesis	**Synthetic Natural Gas (SNG)** Gasification which give high yield product gasses with high methane contents is favourable in Synthetic Natural Gas (SNG) production. SNG has the similar properties as natural gas which produced by methanation of H_2 and CO as the producer gas from gasification.

Application	**Description**
Other Applications	Few applications of syngas are available in the market yet are still under development, such as mixed alcohols, CO production, olefins and aromatics productions.

2.3 Gasification System & Types

Gasification system is not a new established process technology. In gasification system, several kinds of feedstocks are considerable to be converted into valuable fuels, such as many types of wood, agricultural residues, peat, coal, anthracite, oil residues and municipal solid waste may be taken into account (Prins et al., 2007). Complete combustion of biomass will produce N_2, CO_2, H_2O and surplus of O_2. In gasification, which is defined as a partial combustion of solid fuel, have the products of combustible gases, to be named H_2, CO_2, CH_4 and also solids such as tar and dust (Rajvanshi, 1986). Gasification requires temperatures of about 800°C to 1200°C and is carried out in closed top or open top gasifiers, operated at atmospheric pressure or higher (Sharma et al., 2014).

There are several types of gasifiers, developed mainly in Europe and the USA, which are responsible to produce low and medium heating-value gases from biomass (Chmielniak, 2003). The main focus of gasifier's design is to create conditions such that biomass is reduced to charcoal (char) and char is converted at suitable temperature to produce CO and H_2 which are known as syngas (Rajvanshi, 1986). The selection of one type of gasifier over the others is based on the type of fuel, its final available form, its size, moisture content and ash content (SERI, 1979). Hence, it is vital to study all major type of gasifiers available in the current market so to decide the best gasifier to fit the market's demand in the future. There are several major gasifiers have been successfully demonstrated and commercialised, such as fixed bed, fluidised bed and entrained flow bed (Bridgwater, 2006). Figure 2-2 has illustrated fixed bed which has been categorised in updraft and downdraft, together with fluidised and entrained flow beds. These three main gasifiers will be discussed in detailed.

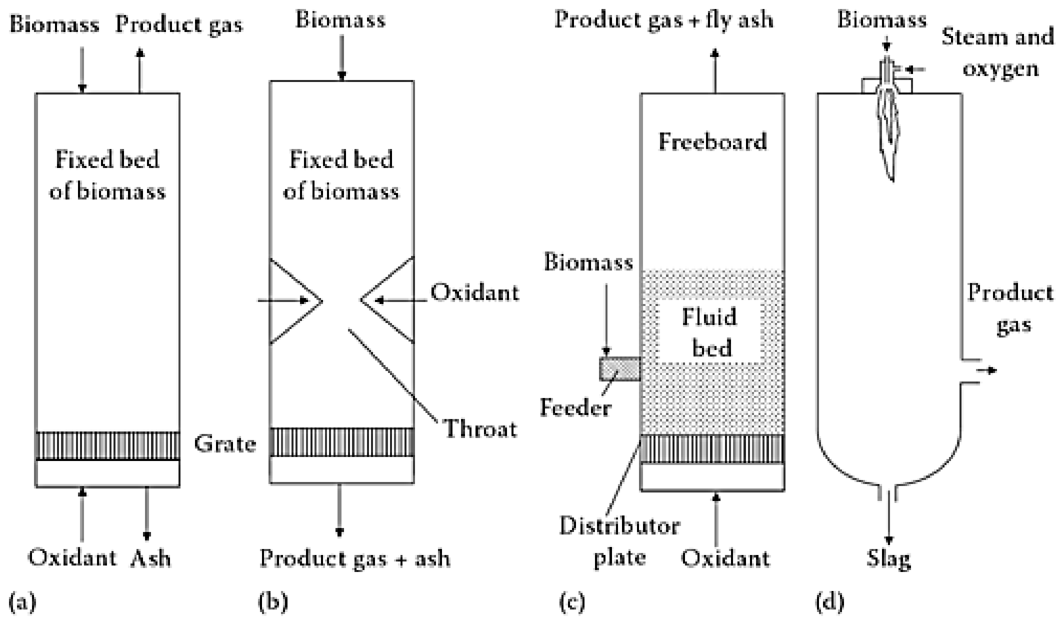

Figure 2-2: General types of gasifiers: (a) updraft fixed bed, (b) downdraft fixed bed, (c) fluidised bed, and (d) entrained flow bed (Kreith & Krumdieck, 2014).

2.3.1 Fixed (Moving) Bed Gasifier

Figure 2-2(a) and 2-2(b) refer to two types of available fixed bed gasifier – updraft and downdraft respectively. Moving-bed gasifiers, which is also called as fixed-bed, are characterised by operation in a bed where the feedstock moves slowly downward pulling by gravity as it is gasified by a blast (Maxim et al., 2010). The main drawback of using fixed-bed gasifier is that syngas contains certainly high levels of phenols, methane and tars (Maxim et al., 2010). The operating temperature of the fixed-bed gasifier with the traditional setup is around 1000^{o}C (Gandhi et al., 2012). There are three major types of fixed-bed gasifier, consisting of updraft, downdraft and cross-draft gasifier.

Updraft fixed-bed gasifier is also known as counter current gasifier. It is the oldest form of gasifier with the simplest configuration, which is still currently being used in industry today. This type of gasifier is easy to be operated and relatively inexpensive (Klass, 1998). The biomass is introduced at the top of the gasifier and there is a grate at the gasifier’s bottom to support the reacting bed (Gandhi et al., 2012). Near the grate at the bottom the combustion reactions occur, followed on next with reduction reactions at higher level in the reactor (FAO Forestry Department, 1986). Heating and pyrolysis of the feedstock happen in the upper part of the gasifier, as a result of heat transfer by forced convection and radiation from the lower levels (FAO Forestry Department 1986).

Figure 2-3 shows the schematic diagram of gasification process stages occur in updraft gasifier. The air or steam enters from the gasifier's bottom. Combustion reactions of feedstock happen at the grate near the gasifier, which are followed by reduction reactions which have higher level up in the gasifier (FAO, 1986). In the upper part of the gasifier, heating and pyrolysis occur as a result of heat transfer by forced convection and radiation from the lower zones (FAO, 1986). Producer gas which carry tars and volatiles along to flow out from gasifier at top of it from lower temperature zone. The produced ashes resulted from combustion will be removed from the gasifier's bottom.

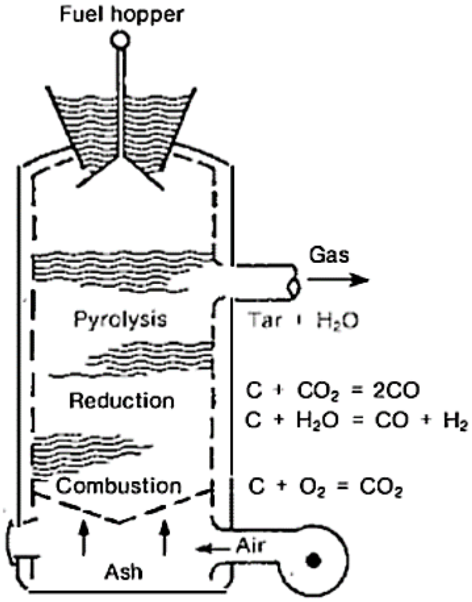

Figure 2-3: Schematic diagram of updraft gasifier showing reactions occurring in each zone (Reed, 1981).

Downdraft gasifier has also the name of co-current gasifier. In co-current gasifier, both biomass and gasifying agent will enter in the downward direction and experience the similar array of reactions, starting from drying, devolatilisation, combustion and reduction (Wang, 2014). The combustion zone is above the reduction zone in co-current gasifier, which is shown in Figure 2-4. The condensable hot gases released from pyrolysis will flow to the bottom and react through the char bed (Cateni, 2008). Downdraft gasifier is designed to solve the problem of excessive tar production, in which primary gasification air is introduced at or above the oxidation zone in the gasifier (FAO, 1986). Due to the downward flow of the syngas, most of the tars will crack into lighter permanent gases at high temperature which is about 1000°C in the combustion zone, giving the result of low tar content in the producer gas (Wang 2014).

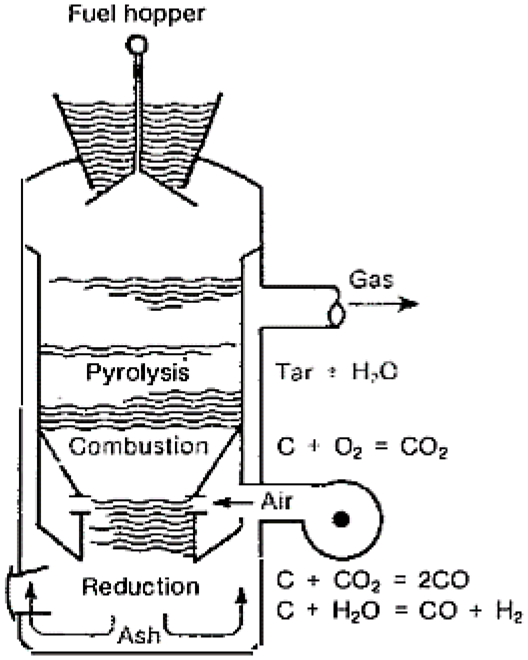

Figure 2-4: Schematic diagram of downdraft gasifier showing reactions occurring in each zone (Reed, 1981).

Downdraft gasifier has the advantage of low tar production yet it suffers from the problem of high ash content fuels. The tendency for slagging or sintering of ash can be solved using rotating ash grates or similar mechanism (Kreith & Krumdieck, 2014). Besides, a major drawback of it lies in its inability to operate on a certain amount of unprocessed fuels. To be specific, fluffy, low density materials will cause flow problems and excessive pressure drop, in addition the solid fuel must be pelletized or briquetted before use (FAO, 1986).

Cross-draft gasifier is shown in Figure 2-5. The feedstock enters from the top of the gasifier, while the gasifying agent is introduced from either one sidewall of the reactor and producer gas will be drawn off from the opposite sidewall of the reactor (Wang, 2014). Sadaka & Eng have suggested that the gasifying agent's velocity is considerably higher as it is introduced into the combustion zone in this reactor, which creates a hot combustion zone. Cross-draft gasifiers respond rapidly to load changes yet insensitive towards biomass composition and moisture content. This design is useful in small-scale operations. Cross draft gasifiers have the quickest response time and the smallest thermal mass of any gas producers because there is a minimum inventory of hot charcoal (Reed & Das, 1988).

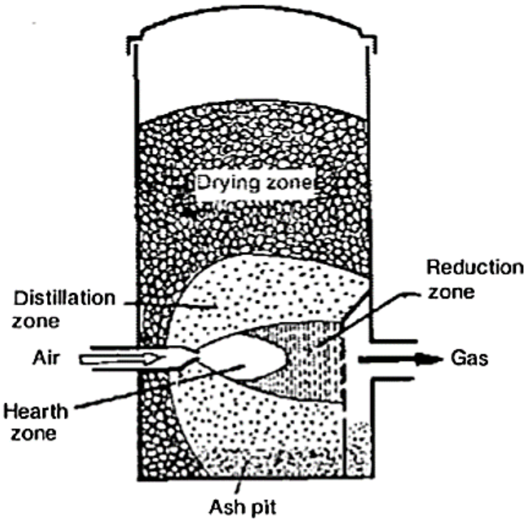

Figure 2-5: Diagram of cross-draft gasifier (Skov, 1974).

These three major types of fixed-bed gasifier have respective advantages and disadvantages, which have been generally summarised in Table 2-2. These unique features of fixed-bed gasifier have decided their function in industry.

Table 2-2: Summary of pros and cons of different classes of fixed-bed gasifier (Rajvanshi, 1986).

Gasifier Type	Advantages	Disadvantages
Updraft Fixed-Bed Gasifier	• Low pressure drop • High thermal efficiency • Little tendency in formation of slag	• High sensitivity to tar, moisture and fuel's moisture content. • Relatively long time needed to start up IC engine • Poor reaction capability with heavy gas load.
Downdraft Fixed-Bed Gasifier	• Flexible adaption of gas production to load • Low sensitivity to charcoal dust and fuel's tar content.	• Tall design • Not feasible for fuel with small particle
Cross-draft Fixed-Bed Gasifier	• Short design • Fast response time to load • Flexible gas production	• Very high sensitivity to slag formation • High pressure drop

2.3.2 Fluidised-Bed Gasifier

Currently, fluidised bed gasifiers are available on a semi-commercial basis from a certain group of manufacturers in U.S.A and Europe (FAO, 1986). There are two types of fluidised-bed gasifiers, consisting of bubbling fluidised-bed (BFB) and circulating fluidised-bed (CFB). Fluidised bed gasifier is able to handle and process a wide range of fuels including those with high moisture content and small particle size. Fluidised bed gasifier is easily to be scaled up for electrical power production (Kreith et al., 2011). Compared to other gasifier types, the fluidised bed gasifier has strong gas to solids contact which is caused by the bubbling phenomena, excellent heat-transfer characteristics, better temperature control, large heat storage capacity, good degree of turbulence, and high volumetric capacity (Sadaka, 2008). Besides, fluidised bed gasifier has better flexibility in terms of feed rate and composition too compared to downdraft fixed bed (Rajvanshi, 1986).

Bubbling fluidised bed gasifier (BFB) consists of a cylinder which contain fine inert particulates of silica sand or alumina, chosen for density, size and thermal properties, resting on a perforated plate (Cateni, 2008). Figure 2-6 illustrates the general design of BFB gasifier. Gasifying agent such as air or steam is forced through the inert particles, until a point is reached when the frictional force between the particles and the gas counterbalances the solids' weight (Ciferno & Marano, 2002). At this gas velocity, minimum fluidisation will happen, bubbling and channelling of gas through the media occurs, result that the particles remain in the gasifier and appear to be in a "boiling state" (Craig et al., 1996). The biomass feed will be broken up by the fluidised particles at the bed to ensure good heat transfer throughout the gasifier (Ciferno & Marano, 2002).

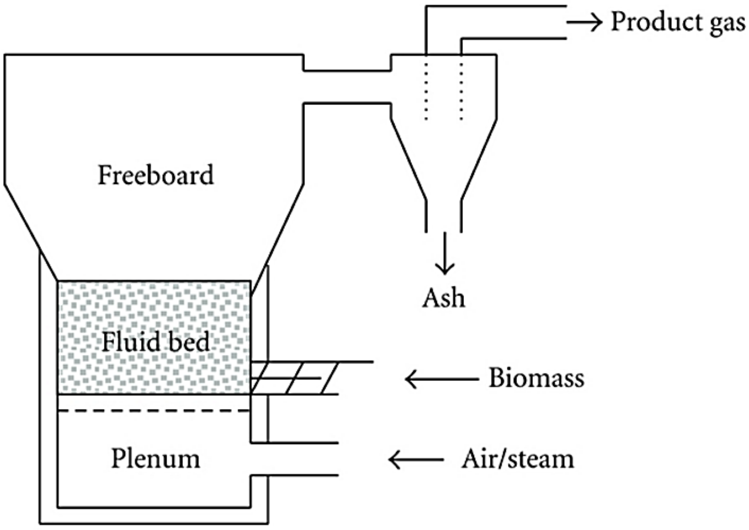

Figure 2-6: Schematic illustrative diagram of a bubbling fluidised bed gasifier (Williams et al., 2007).

For circulating fluidised bed (CFB) gasifiers, the operation is carried out at gas velocities that higher than the minimum fluidisation point, causing entrainment of the particles in the gas stream (Rajvanshi, 1986). The entrained particles in the gas product is then collected at top of the reactor, followed by separation in a cyclone, and returned to the gasifier (Ciferno & Marano, 2002). Ideally, the fuel particles have small size enough to totally react before being transferred into the cyclone, yet in real practice, large fuel particles recirculate with bed media until small and light enough to be carried out with the producer gas exiting the cyclone or other separation device (Williams et al., 2007). CFB usually offers higher efficiency and conversion rate compared to the others. An illustration of CFB gasifier is shown in Figure 2-7.

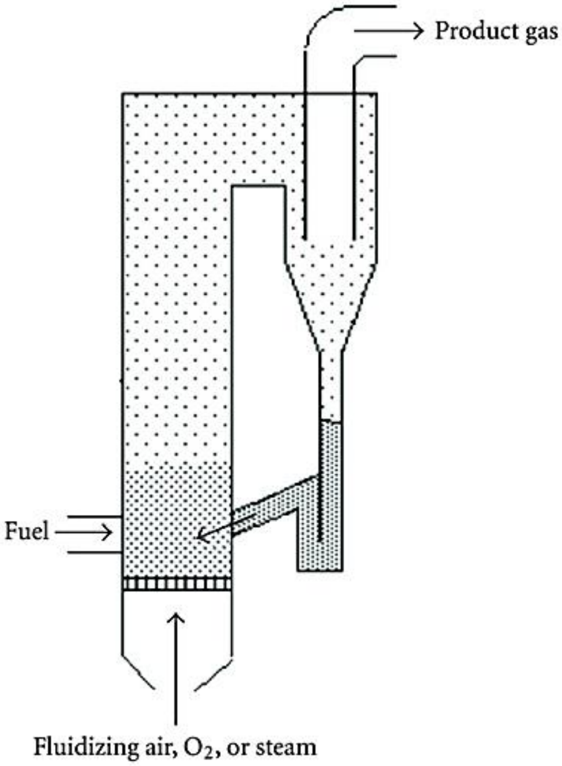

Figure 2-7: Schematic illustrative diagram of a CFB gasifier (Williams et al., 2007).

2.3.3 Entrained Flow Gasifier

There are numerous entrained flow gasifiers which could be seen in the current industrial market, such as Conoco-Phillips E-Gas, GE (formerly Texaco), Shell, PrenfloTM, MHI, Siemens and MPG gasifiers (Breault, 2010). The entrained-flow gasifier can be considered as a highly efficient reactor which was developed initially for steam-oxygen gasification of coal at temperature 1200^{o}C – 1500^{o}C to assure high char conversion towards 99% and low tar production and also to convert the ash to molten slag (Kreith & Krumdieck, 2013). The operation temperature is generally set as high level due to the short residence time, which is ranged from seconds to tens of seconds, and also to ensure a high carbon conversion from the process of rapid heating between coal and gasifying agent. Hence, most entrained flow gasifiers use oxygen rather than air and operate beyond the slagging temperature of the coal, which is at around 1150°C (Phillips, 2006). According to NETL, entrained-flow gasifiers have the ability to handle practically any coal feedstock regardless of rank and to produce a clean, tar-free synthesis gas, in addition to melt the coal ash into vitreous inert slag which is easily to be disposed at this high level of operation temperature.

Figure 2-8 shows the schematic drawing of entrained flow bed gasifier in general. It can be seen that finely-ground coal enters the reactor in co-current flow with the gasifying agent. This reactor is available in much larger capacities (> 100MWe) than other variants, but these are more commonly used for fossil fuels like refinery wastes, coal, etc. which usually required to be fine particles (Basu, 2006).

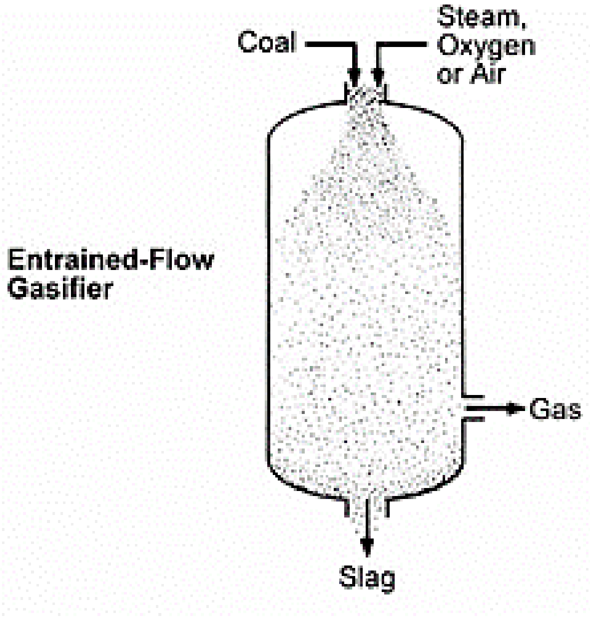

Figure 2-8: Diagram of a generic entrained flow gasifier (Source: Electric Power Research Institute).

2.3.4 Interest of Study in Gasifier

Several types of gasifiers have been discussed in detailed. Based on the brief description, each of them has own uniqueness and function in particular field and market. Table 2-3 basically represents the summary of configurations for each type of gasifier. Selecting entrained flow bed as the gasifier in this research paper is because the ability to have coals regardless of rank with high throughputs per reactor volume and the simpler mechanical design with nearly complete carbon conversion into producer gas (Guo, 2007).

Table 2-3: Several selected gasifiers with respective configurations (Breault, 2010).

	Moving Bed		**Fluidised Bed**		**Entrained Flow**
Ash Condition	Dry	Slagging	Dry	Agglomerate	Slagging
Coal Feed	~ 2 in	~ 2 in	~ 0.25 in	~ 0.25 in	100 Mesh
Fines	Limited	Better than dry ash	Good	Better	Unlimited
Coal Rank Gas Temperature (F)	Low	High	Low	Any	Any for dry feed
Oxidant Requirement	Low	Low	Moderate	Moderate	High
Steam Requirement	High	Low	Moderate	Moderate	Low
Issues	Fines and hydrocarbon liquids		Carbon conversion		Raw gas cooling

Entrained flow bed will be the interest in this research paper as it is not only commercially available on large scale (mainly for coal and liquid fuels), which means that it is capable to generate power in large scale. Table 2-4 shows the strengths and weaknesses of each type of gasifier together with their respective power production scale. It also can achieve the highest efficiency from biomass to syngas. According to NETL, it is worth to investigate entrained flow as it has all the increased importance to address the issues associated with co-gasification.

Table 2-4: A comparison table of fixed, fluidised and entrained bed gasifiers with specific reference to coal gasification (Basu, 2006).

Class	Types	Strength / Weakness	Power Production
Fixed Bed	Downdraft	Low heating value, moderate dust, low tar	Small to medium scale
	Updraft	Higher heating value, moderate dust, high tar	
	Cross-draft	Low heating value, moderate dust, high tar	
Fluidised Bed	Bubbling or Circulating	Higher than fixed bed throughput, improved mass and heat transfer from fuel, higher heating value, higher efficiency	Medium scale
Entrained Flow		Can gasify all type of coal, large sensible heat in flue gas, large capacity, involves slagging of ash	Large scale

2.3 Gasification Process

2.3.1 Gasification Reactions

The gasification of biomass is considered to be complex due to the composition of producer gas is varied with the types of biomass. Generally, regardless of the type of gasifier, the processes occurring in any gasifier include drying, pyrolysis, reduction, and oxidation, where these processes may occur simultaneously or sequentially depending on the reactor design (Erakhrumen, 2012). The reactions are generally performed at elevated temperatures, ranged from 500°C – 1400°C, and at atmospheric pressure or elevated pressures up to 33 bar (Ciferno & Marano, 2002).

Drying or dehydration is the first stage occurring in gasifier, where the water content in the compacted solid particles of feedstock will be dried out after heated below 100°C (Kreith & Krumdieck, 2014). This process often can be performed by using waste heat or solar energy to dehydrate the feedstock of biomass containing more than 25% moisture (wet basis) before gasification takes place (Reed & Das, 1988). It is recommended that biomass moisture content should be lower than 10 – 15% prior to gasification (McKendry, 2002).

Pyrolysis is the next stage after drying process, which is also known as devolatilisation, is the decomposition of the dried biomass feedstock by heat. Products from pyrolysis depend on temperature, pressure, feedstock, residence time and heat loss. This process is endothermic and 75 to 90% volatile materials are produced in the form of gaseous and liquid hydrocarbons (Erakhrumen, 2012). This process has an ideal temperature ranging from 400^oC to 500^oC, where a rapid thermal anoxic degradation of the carbonaceous materials take place. As the solid fuel is heated to 300^oC – 500^oC in the absence of oxidising agent, the dried biomass will decompose into organic vapours, producer gases such as CO_2, H_2, CH_4, solid carbon (char) and tars (Bridgwater, 1995).

The products of gasification (H_2O, CO_2 and unburnt partially cracked pyrolysis products) will pass through a red-hot charcoal bed where the reduction reactions take place after pyrolysis (Rajvanshi, 1986). Table 2-5 summarises the main gasification reactions occur which involve volatiles and char (Velez et al., 2009; Heiskanen, 2011).

Table 2-5: Main reactions of gasification processes with respective heat of reaction, ΔH_R (Bassyuoni, 2014).

Name of Reaction	**Reaction**	**ΔH_R at 25°C (kJ/mol)**	**Equation**
Heterogeneous Reactions			
Complete Combustion	$C + O_2 \rightarrow CO_2$	-394	2.1
Incomplete Oxidation	$C + 1/2\ O_2 \rightarrow CO$	-283	2.2
Water-Gas	$C + H_2O \rightarrow CO + H_2$	+131	2.3
Boudouard	$C + CO_2 \rightarrow 2CO$	+172	2.4
Hydrogasification (Methanation)	$C + 2H_2 \rightarrow CH_4$	-74.8	2.5
Homogeneous Reactions			
Water-Gas Shift	$CO + H_2O \rightarrow CO_2 + H_2$	-41.2	2.6
Ammonia Formation	$N_2 + 3H_2 \rightarrow 2NH_3$	-46.1	2.7
Hydrogen Sulphide Formation	$S + H_2 \rightarrow H_2S$	-21	2.8
Methane-Steam Reforming (Lahijani & Zainal, 2011)	$CH_4 + H_2O \rightarrow CO + 3H_2$	+165	2.9

Temperature in reduction zone normally to be in the range from 100°C – 1000°C. Reactions of eqn. 2.3 and eqn. 2.4 are the main reduction reactions and being endothermic that has the capability of decreasing gas temperature (Rajvanshi, 1986). There are several possibilities for the kinetics rate equations, hence first order reaction with respect reacting species has been selected for Eqn. 2.1 to Eqn. 2.7, which has been demonstrated in Eqn. 2.8 (Inayat et al., 2010).

$$r_i = k_i C_a C_b \qquad \text{(Eqn. 2.10)}$$

Where, *r* equals to rate of reaction; *C* represents concentration; *k* is the rate constant; *i* is species; *a* & *b* refer to chemical substances.

The kinetics parameters of rate constant equation which is varied with temperature, used for all reactions from Eqn. 2.1 until Eqn. 2.9 are illustrated in Table 2-6. The general rate constant equation is stated as Eqn. 2.11.

$$k = Ae^{-E_a/(RT)} \qquad \text{(Eqn. 2.11)}$$

Where k is rate constant, A is pre-exponential factor, E_a is activation energy, R is universal gas constant (8.31446 J mol^{-1} K^{-1}), T is thermodynamic temperature in Kelvin.

Table 2-6: Kinetics parameters of rate constant equation for Eqn. 2.3 to Eqn. 2.7 from several literatures.

Equation	**A (s^{-1})**	**E_a (J)**	**References**
2.1	-	-	-
2.2	5.67×10^9	1.60×10^8	(Lee et al., 2014); (Blasi, 2000)
2.3	4.40×10^9	1.62×10^8	(Inayat et al., 2010)
	2.20×10^{12}	1.67×10^8	(Lee et al., 2014); (Westbook & Dryer, 1981)
2.4	2.00×10^5	6×10^3	(Inayat et al., 2010)
	1.00×10^{14}	4.20×10^7	(Lee et al., 2014); (Blasi, 2000)
2.5	1.20×10^9	1.8×10^4	(Inayat et al., 2010)
	1.60×10^{12}	2.24×10^7	(Lee et al., 2014); (Freund, 1986)
2.6	1.33×10^3	1.75×10^7	(Lee et al., 2014); (Wang & Brennan, 1995)
2.7	3.00×10^5	1.50×10^4	(Inayat et al., 2010)
2.8	2.78×10^3	1.26×10^7	(Lee et al., 2014); (Blasi, 2000)
2.9	4.40×10^{11}	1.68×10^8	(Lee et al., 2014); (Watanabe & Otake, 2006)

Equations 2.1 and 2.2 can be combined into single equation (Eqn. 2.12), which represents the combustion reaction in the gasification process (Nikoo & Mahinpey, 2008).

$$C + \alpha O_2 \rightarrow 2(1 - \alpha)CO + (2\alpha - 1)CO_2 \qquad \text{(Eqn. 2.12)}$$

In this research work, α is a mechanism factor that changes from 0.5 to 1.0, when CO or CO_2 is carried away from the char particle during char combustion. The factor, α, is a function of the temperature and average diameter of the char particles (Rajan & Wen, 1980; Nikoo & Mahinpey, 2008). In the model proposed by Nikoo and Mahinpey (2008), the value of α is equal to 0.9. Hence, in this research work, same value will be employed for α as well, to form equation 2.13.

$$C + 0.9O_2 \rightarrow 0.2CO + 0.8CO_2 \qquad \text{(Eqn. 2.13)}$$

The kinetic parameters for Equation 2.13 is obtained from Nikoo and Mahinpey (2008), where the E_a/R equals to 13,523K while A equals to $0.046 s^{-1} atm^{-1}$.

The overall processes occur in a gasifier is illustrated in Figure 2-9, where it is started from char gasification and end with water shift gas reaction.

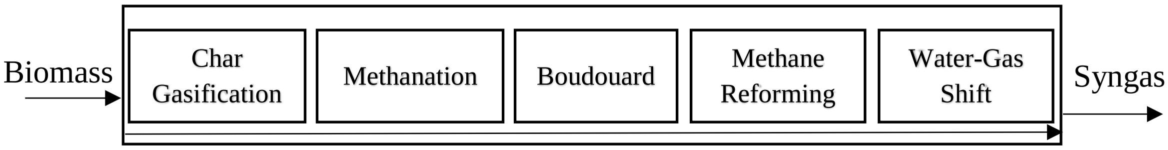

Figure 2-9: Process block diagram of gasification.

As shown in Figure 2-9, the feedstock, biomass, enters into gasifier will firstly experience char gasification after pyrolysis. At char gasification, the carbon content of biomass will react with limited supply of air to produce a certain amount of CO and CO_2. The process is followed by methanation (hydrogasification) where the methane is produced, boudouard, methane reforming as minor reaction and water-gas shift (WGS) reaction. All these reactions happen at once in entrained flow gasification under high temperature.

2.3.2 Gasification Products

Biomass gasification will give the gaseous products, which is also known as syngas, consist primarily of H_2 and CO, followed by lesser amounts of CO_2, H_2O, CH_4, higher hydrocarbons (C_xH_y), N_2, and the other particulates (Ciferno & Marano, 2002). Table 2-7 shows the general syngas composition from a few common available gasifiers. The composition is dependent on the equilibrium degree attained by various gas phase reactions (Sadaka, 2009). The typical producer gas composition of EF gasification of woody biomass with 7% moisture compared to product gas compositions from a direct Ccfb gasifier at 850ºC and various conditions. Table 2-8 shows another general syngas composition of different types of gasifiers at various conditions.

Table 2-7: General syngas composition from several selected types of gasifiers (Kreith & Krumdieck, 2013).

Gasifier Type	**Gaseous Constituents (vol. % dry)**					**HHV (MJ/m^3)**	**Gas Quality**	
	H_2	CO	CO_2	CH_4	N_2		Tars	Dust
Air-blown updraft	11	24	9	3	53	5.5	High (~10g/m^3)	Low
Air-blown downdraft	17	21	13	1	48	5.7	Low (~10g/m^3)	Medium
Air-blown fluidised bed	9	14	20	7	50	5.4	Medium (~10g/m^3)	High
Oxygen-blown downdraft	32	48	15	2	3	10.4	Low (~10g/m^3)	Low
Indirectly heated fluidised bed	31	48	0	21	0	17.4	Medium (~10g/m^3)	High

Table 2-8: General syngas composition of gasification at various types of gasifers and conditions (Boerrigter & Rauch, 2005).

Gasification Process		**CFB**	**CFB**	**CFB**	**EF**	**EF**
Pressure [bar]		1	1	20	1	20
Gasifying agent		Air	O_2/steam	O_2/steam	O_2	O_2
Hydrogen	Vol%	14	32	19	33	27
Carbon Monoxide	Vol%	21	27	20	53	53
Carbon Dioxide	Vol%	14	29	40[a]	13	19[a]
Methane	Vol%	5	8	15	0	0
C_{2+} Hydrocarbons	Vol%	2	3	5	0	0
Benzene	Vol%	0.4	1	1	0	0
Nitrogen	Vol%	44	0	0	0	0
Tar (wet gas)	g/m_n^3	8	8	11	0	0
H_2O	$Vol\%_{wet}$	11	28	30	19	22
LHV (Dry Gas)	MJ/M_n^3	7.7	12.4	14.9	10.3	9.6

[a.] In pressurised gasification CO_2 is used for inertisation of the feed to prevent nitrogen dilution of the gas.

2.3 Co-gasification System

Co-gasification which means combined gasification, with using biomass and coal, allows the achievement of profitability of production, operational stability, minimising the environment footprint and also optimal thermal efficiency for the process (Chmielniak, 2003).

Energy resources in the context of fuels from the gasification of biomass, which is normally a waste product from agriculture activity and forestry, is considered much favourable since it is a conversion from solid waste into valuable energy. The most obvious beneficiary in utilising biomass will be the developing countries whose economies are dependent on agricultural production and are facing insufficiency in conventional fuels (Boateng et al., 1992). A promising way to use biomass for production of heat, electricity, and other biofuels is through biomass gasification (Karamarkovic, 2010). However, solely biomass gasification is relatively high-cost and relatively large amount of tar which has low value will be produced, therefore, co-gasification is suggested so that the cost of the feedstock can be reduced while minimising the problems that occur in plant operation due to the production of tar (Kumabe et al., 2006).

2.4 Feedstock - Biomass

Biomass is a potential resource to be considered in overcoming the global energy demand issue in recent time. Biomass power plants exist in over 50 countries around the world and supply a certain raising quantity of electricity (Baños et al., 2011). Renewables Global Status Report in 2010 had indicated that European countries are expanding their total share of power from biomass, such as Austria (7% of the renewable energy generation), Finland (20%), and Germany (5%). Undoubtedly that biomass has great potential as a clean, renewable feedstock for producing modern energy carriers (Ptasinski et al., 2007). Biomass gasification always the major problem of tar formation to deal with, which will lead to blocking and fouling process equipment such as turbines and engines after it has condensed at reduced temperature (Devi et al., 2003). Biomass is one of the most promising renewable energy sources, but more research is needed to prove that power generation from biomass is both technically and economically feasible (Baños et al., 2011). The use of vegetable biomass from greenhouse residues had been proposed to generate electrical energy via the process of gasification (Agugliaro, 2007). The increasing interest of biomass gasification have produced some models in explaining and presenting the design, simulation, optimisation and process analysis of gasifiers (Puig-Arnava et al., 2010).

2.4.1 Woody Biomass

In gasification, where wood is the feedstock, is a high temperature reaction and small amounts of tar mainly composed of hydrocarbon-type compounds will be produced (Elliot & Baker, 1986). The use of producer gas from wood gasifiers, which could be used in modern devices such as gas turbines, fuel cells or catalytic reactors, is still limited (Prins et al., 2006). Woody biomass can be categorised into few types, such as wood chips, wood sawdust, cedar wood and others as well. Each type of wood will give different composition of producer gas and require different type of gasifier. Wood industry in Malaysia has accounted a portion of 3.7% from the overall biomass amount (Umar et al., 2013).

2.4.2 Empty Fruit Bunches (EFB)

In Malaysia, oil palm planted area, crude palm oil (CPO) production, import, export and closing stocks have shown a steady growth up until 2015 (MPOB, 2016). In 2014, Malaysian Palm Oil Council (MPOC) has reported that Malaysia currently accounts for 39 % of world palm oil production and 44% of world, playing the role in fulfilling the growing global need for oils and fats. EFB is an attractive type of biomass to be investigated as the feedstock together with coal in co-gasification to produce high hydrogen content syngas. It can be illustrated that EFB is a very convincing feedstock for gasification due to its high supply and production in Malaysia and its potential component to be extracted and processed in generating energy to meet the demand.

Components and composition of EFB are useful in determining the methodology of process simulation, which have been briefly stated in Table 2-9 based on the ultimate analysis on EFB from experimental work (Betty, 2015).

Table 2-9: Ultimate analysis on EFB (Betty, 2015).

Element	Mass (%)	Mole with 100g basis
C	43.518	3.623
H	7.225	7.197
N	3.041	0.217
S	0.290	0.009
O	45.896	2.869

The chemical components in EFB consist mainly of C, H, N, O and S. From the ultimate analysis, the empirical formula of EFB can be defined as $CH_{1.986}O_{0.792}N_{0.06}S_{0.002}$ with C as the chemical basis due to its primary significance.

2.4.3 Rice Husk

Rice husk is one of the popular feedstocks for gasification. The total annual rice production in the world is approaching 500 million tonnes in 1996 (FAO, 1996). The global rice production in 2007 was even found approximately 638 million tonnes and Malaysia's contribution was 2.2 million tonnes from it (Johnson & Yunus, 2009). This has proven the continual growth and it is projected to grow exponentially with the increasing population worldwide. The annual rice husk production is about 100 million tonnes with making the assumption of 20% of rice husk recovery rate from rice gains. Converting rice husks into gaseous or liquid fuels will be a great advantage to countries which are lacking of conventional energy resources and whose economic development is contributed by agriculture and local industries (Mansaray, 1999). Rice husk as one of the biomass will cause waste disposal problem and hence with performing gasification would help in eliminating the environmental problem and reduce the existence of hazards caused by the huge amount of rice husk. At the same time, energy generation can be achieved. However, Malaysia is not a prominent rice-producing country (Johnson & Yunus, 2009), hence gasification of using rice husk as feedstock is not so favourable compared to the others such as EFB.

2.5 Coal

Coal is one of the feedstocks in co-gasification. Coal is normally classified into three major types, comprising of anthracite, bituminous and lignite. Coal is also further classified as semi- anthracite, semi-bituminous, and sub-bituminous (Jain, 2013). Table 2-10 shows one of the composition analysis on coal by Jain (2013). It obviously shows that comparing to biomass, coal has a higher percentage of fixed carbon content and lower S and N contents. Biomass has a relatively low calorific value, which is not beneficial for gasification (Prins et al., 2007). Thus, the introduction of coal to be mixed with biomass in co-gasification can be a process with negligible additional irreversibility. In this research study, Adaro coal has been chosen for the process simulation of coal feedstock in co-gasification owing to its analysis data availability and cheap cost imported from Indonesia.

Table 2-10: Analysis data for two types of coal (Jain, 2013).

	Indian Coal	**Indonesian Coal**
Type	Bituminous	Bituminous
Proximate analysis		
Moisture	5.98	9.43
Ash	38.63	13.99
Volatile matter	20.70	29.79
Fixed carbon	34.69	46.79
Total	100.0	100.0
Ultimate analysis		
Moisture	5.98	9.43
Carbon	41.11	58,96
Hydrogen	2.76	4.16
Oxygen	9.89	11.88
Nitrogen	1.22	1.02
Sulfur	0.41	0.56
Ash	15.8	5.7
Total	100	100

2.6 Previous Literature Works

There are many researches done on the gasification process to study its feasibility and practicality via experiment, simulation and modelling works. Extensive studies have been found in the literature on pure biomass gasification and pure coal gasification. Co-gasification becomes another interest of researcher to tackle on as it provides numerous benefits in terms of its environmental advantage despite its technical challenges. However, in fact, there are limited researches conducted on the co-gasification of biomass and coal, and there is an apparent lack of fundamental understanding of the interactive effects of coal and biomass during the co-gasification (Xu, 2013). In addition, there is no comprehensive mathematical model available in the literature on co-gasification.

Basically the study of co-gasification process parameters currently includes but not limited to temperature, pressure, feed flowrate, S/B ratio, B/C ratio, ER, co-blending effect and gasifying agents. These manipulated variables directly affect the product gas composition, heating value and both the biomass and coal conversion efficiency. Extensive studies have been found in the literature on pure biomass gasification and pure coal gasification.

2.6.1 Coal Gasification

For coal gasification, relevant extensive researches can be found as well as biomass gasification. Most of the previous studies are concerned with the performance of coal gasifier and proposal in enhancing the efficiency.

Wang et al. (2010) has performed simulation of 10 tons/hr of coal in dual-bed coal gasification using ASPEN PLUS for evaluating the performance of the system. The result indicates a strong possibility of scale-up using a fluidised bed gasifier. The work indicated that it is possible to produce a middle caloric fuel gas with dual-bed gasification technology using granular coal with sizes less than 20 mm.

Kong et al. (2013) developed a three stage equilibrium model for coal gasification in the Texaco type coal gasifiers based on ASPEN PLUS to calculate the composition of syngas, carbon conversion and gasification temperature. Good agreement is obtained from the validation between the model results and experimental data.

Dai et al. (2017) introduced a novel process for the integration of pyrolysis and entrained-flow gasification for the as-mined Victorian brown coal containing 65 wt.% moisture and the exergy efficiency is investigated. The result shows that the addition of 20% of black coal is the optimum ratio to improve the ash slagging propensity, as well as improve exergy efficiency compared to the conventional drying–gasification process.

Tanner et al. (2015) studied the entrained flow pyrolysis and gasification of a Victorian brown coal to investigate the feasibility of the system and char conversion and syngas yield. Entrained flow processing of this fuel is proven to be technically viable and the char conversion and syngas yield increased with increasing gasification temperature.

A steady state simulation of syngas production from gasification process using commercial technologies is performed by Preciado et al. (2012) using Aspen Plus as simulator, with bituminous coal obtained from the Colombian Andean region as the feed. The syngas molar composition and overall CO conversion are analysed and reported that high molar composition of H_2 is attained.

Jang et al. (2013) proposed catalytic coal gasification of Illinois #6 and Indonesian low rank coal with kinetic analysis. The simulation result which has been validated using experimental data and it shows good agreement. However, that model is only applied to a limited case and it should continually be studied for making a global model applicable to various conditions.

Nayak and Mewada (2011) has carried out a process simulation of coal gasification in fluidised bed with using stoichiometric reactor in ASPEN PLUS to investigate the effect of various parameters like S/C ratio and oxygen flow rate effects on product gas composition. A decreasing trend in the product gas composition of all the constituents is observed with the increasing steam flow rate. CO and CO_2 increased while H_2 decreased at small deviation at increasing air flowrate.

Nathen et al. (2008) investigated the preliminary feasibility assessment of gasification of New Zealand (NZ) lignite and sub-bituminous coals using equilibrium model blocks in ASPEN HYSYS. With gasification data on various coals, the result deduced that ignoring ash in the coal composition could be the cause to the discrepancies noticed in the energy balances. A total of 16% more NZ lignite coal is required compared to NZ sub-bituminous coal for a constant 400 MW IGCC power output.

Duan et al. (2015) presented a model for the system of coal gasification with steam and blast furnace slag waste heat recovery by using the ASPEN PLUS. The influence of gasifying temperature and S/C ratio on gas yield, CGE, carbon gasification efficiency (CE) and syngas product efficiency are investigated. Moreover, the mass and energy flow of the gasification system is analysed. From the aspect of CE, PE and CGE, the optimal temperature to simulate gasification reaction and recover the slag heat is 800^oC. Increasing S/C ratio promotes the production of the H_2, yet too much heat from slag will be taken away by steam, which reduces the efficiency of gasification and heat recovery. The analysis shows a balance point of S/C ratio is 1.5 after taking the syngas production and energy cost into consideration.

Dai et al. (2017), Duan et al. (2015), Kong et al. (2013), Jang et al. (2013), Preciado et al. (2012), Nayak and Mewada (2011) and Wang et al. (2010) used ASPEN PLUS as the modelling software in simulating the coal gasification. Only Nathen et al. (2008) used ASPEN HYSYS in simulating coal gasification, which entrained flow bed is used as gasifier. However, kinetic modelling was done only by Jang et al. (2013) and Kong et al. (2013). Jang et al. (2013) has done the research on fixed bed gasifier, while Dai et al. (2017), Tanner et al. (2015), Preciado et al. (2012) and Nathen et al. (2008) had used entrained flow bed as gasifier in the process simulation work. Duan et al. (2015) and Nayak & Mewada (2011) had studied the influence of parameters such as S/C ratio and oxygen flowrate on the composition of syngas at steady equilibrium state.

Table 2-11 shows the summary of previous literature works on coal gasification. In addition, Table 2-12 describes the parameters, gasification types. model blocks, simulation approach and assumptions made on selected models of previous studies on process simulation of coal gasification.

Table 2-11: Summary of previous literature works on coal gasification.

Researcher	**Type of Gasifier**	**Research Approach**	**Simulator**
Dai et al. (2017)	Entrained Flow Bed	Equilibrium	ASPEN PLUS
Tanner et al. (2015)	Entrained Flow Bed	Experiment	-
Duan et al. (2015)	Not specified.	Equilibrium	ASPEN PLUS
Kong et al. (2013)	Not specified.	Kinetic	ASPEN PLUS
Jang et al. (2013)	Fixed Bed	Kinetic	ASPEN PLUS
Preciado et al. (2012)	Entrained Flow Bed	Equilibrium	ASPEN PLUS
Nayak & Mewada (2011)	Fluidised Bed	Equilibrium	ASPEN PLUS
Wang et al. (2010)	Fluidised Bed	Equilibrium	ASPEN PLUS
Nathen et al. (2008)	Entrained Flow Bed	Equilibrium	ASPEN HYSYS

Table 2-12: Selected previous process simulation of coal gasification with the manipulating parameters, gasification type, model blocks description and assumptions.

Reference	Parameters	Gasification Type	Description	Assumptions
Nathen, Kirkpatrick & Young (2008)	1. Coal Type (lignite and sub-bituminous) 2. Temperature	Entrained-Flow	• ASPEN HYSYS is utilized, equilibrium-based. • Package: Modified Peng-Robinson model, PRSV • Modelled using a Gibb’s minimization algorithm. • The reactor is specified with coal, oxygen, and steam as the feed rates. Verification was conducted to determine whether the gasifier produced a gas mixture that was thermodynamically credible, by employing the governing water-gas shift reaction in analysing the outcomes at different pressures and temperatures. • Then, different types of coal were simulated based on the data collated.	• Neglected kinetics due to lacking of info and complexity • All coal compositions were determined on a dry, ash free basis. • Coal is processed into a dried and pulverized form before it enters the gasifier (Shell dry feed, entrained flow gasifier). • Moisture data on an as-received basis can be quite variable given the coal could have been influenced by its environmental conditions such as rain. • Bound moisture is driven off. • The calorific data is also on a dry, ash free basis.

Reference	Parameters	Gasification Type	Description	Assumptions
			• The outlet compositions of CO and H_2 of different coals were then verified against published data.	• The volatile matter is composed of methane and water only.
Kong et al. (2013)	1. Temperature 2. Coal Type 3. Coal feed rate 4. steam to coal ratio 5. oxygen to coal ratio	Entrained-Flow	• ASPEN PLUS is utilized, kinetic-based model. • PR-BM method is used, the enthalpy and density model selected for both coal and ash, which are non-conventional components, are HCOALGEN and DCOALIGT. • Three stage steady-state model is developed for the gasification process. Each stage is represented by the built-in operating units or user defined modules. • In the first stage, coal is pyrolysed and reacting with supplied oxygen until the oxygen is depleted to be zero. These two processes proceed simultaneously,	• The system is at steady sate and isothermal. • Coal devolatilization takes place instantaneously and volatile products mainly consist of H_2, CO, CO_2, CH_4, and H_2O. • Only a part of the supplied water contributes to the equilibrium reaction in the second stage. • Ash is inert. • No oxides of nitrogen are produced.

Reference	Parameters	Gasification Type	Description	Assumptions
			described by a RYield reactor in Aspen Plus. The yield distribution for this process is specified by using a FORTRAN statement in calculator based on mass balance. • In the second stage, the char gasification is modelled using an RGibbs reactor. A separation column model is used before the RGibbs reactor to separate the water in order to perform the calculation of carbon conversion. • In the third stage, all the materials flow into another RGibbs reactor to carry out the calculation of the syngas compositions. A design specification for the temperature leaving the second stage to that leaving the third stage is used to determine the water amount involved in the second stage for the estimation of the carbon conversion.	

Reference	Parameters	Gasification Type	Description	Assumptions
Duan et al. (2015)	1. Temperature 2. Steam to coal ratio	Not Specified.	• ASPEN PLUS is utilized, kinetic-based model. • Coal was decomposed into three elements by RYield reactor and the stream of BF slag was also fed into the reactor to provide the heat needed for the process of the decomposition. • The chemical equilibrium calculation was performed in RGibbs reactor based on the Gibbs free energy minimization method.	• Thermal efficiency of the unit of Cyclone 1–2 and Mixer were 100% in the calculation of the energy efficiency. • The coal components assumed to be present at equilibrium were C, $H_2O(g)$, H_2, CO, CH_4, CO_2.

2.6.2 Biomass Gasification

Pure biomass gasification is widely studied by researches to determine the best kinetic process in maximising the carbon conversion and producing optimum composition of syngas. In the past researches, biomass is not only limited to agriculture waste but also inclusive of household and industrial sectors' municipal disposal.

Zainal et al. (2001) has reported the initial moisture content in the woody biomass and gasifying zone's temperature affect the calorific value of the syngas, with employing equilibrium model of biomass gasification in downdraft gasifier. The research result suggested that the increase of the moisture content in wood and/or the increase of gasification temperature will decrease the calorific value of syngas.

Nikoo and Mahinpey (2008) developed the model of fluidized bed reactor for biomass gasification that comprised both hydrodynamic parameters and reaction kinetic data of char combustion using ASPEN PLUS with the assistance of external FORTRAN subroutines. The developed model is validated with experimental data from the gasification of pine in a lab-scale fluidised bed gasifier. The effect of gasifying temperature, ER, S/B ratio and average particle size of biomass on the composition of syngas together with the carbon conversion efficiency were analysed.

Loha et al. (2011) conducted steam gasification experiment using rice husk as biomass feedstock in fluidised bed gasifier. The influence of gasification temperature and S/B ratio on the composition of syngas were investigated using equilibrium model. The correlation of H_2 yield from biomass at difference temperature and S/B ratio is formulated.

Ramzan et al. (2011) studied the potential of biomass gasification with using different feedstocks comprising of food waste, municipal solid waste and poultry waste. Biomass gasification model is developed using ASPEN PLUS simulator to investigate the effect of operating parameters inclusive of gasifying temperature, ER, biomass moisture content and steam injection on the composition, HHV, cold gas efficiency (CGE) and H_2 production of the syngas.

Mitta et al. (2006) developed gasification model using ASPEN PLUS to investigate the possibility of waste tyre gasification. The modelling result is compared with the data from pilot plant test and used to study the influence of temperature on the composition of the produced gas. Modified process configuration is also recommended to improve the process performance in the research.

The study of gasification using palm oil fronds is studied by Atnaw et al. (2013). The research result found that the heating value of syngas and the value of cold gas and carbon conversion efficiency were comparable with woody biomass. From the research done by Gai et al. (2014), ER and S/B ratio were reported to have a significant effect on the distribution of gaseous chlorides.

Shen et al. (2008) suggested that biomass gasification in interconnected fluidized beds which separated the combustion and gasification sections would cause both high H_2 yield and relative great hydrogen content. ASPEN PLUS model is developed to study the significance of operating conditions in gasification and the preferable condition is recommended.

Bassyouni et al. (2014) has developed a gasification system with date palm leaves as feedstock using ASPEN HYSYS as simulator. The syngas composition is validated with experimental data. The influence of gasifying temperature and S/B ratio were thoroughly analysed. The proportion of synthesis gas composition increases as temperature increases. CO_2 and CH_4 in the product gases are also found to decrease with increasing temperature. At 800^oC, the exit gas reaches a stable molar composition. Increasing steam to biomass ratio increases CO_2 and H_2 at the expense of CO, governed by shift reaction. Steam induction increases the methane contents, thereby improves the heating value of the product gas.

Im-orb et al. (2016) conducted a comprehensive analysis of rice straw gasification with varying the gasifying agents using a thermodynamic model-based approach developed in ASPEN PLUS. The equilibrium model proposed that steam-CO_2 gasification gives high syngas productivity and low H_2/CO ratio while steam-air gasification needs less energy and can be conducted at a thermal-neutral zone.

He et al. (2012) simulated biomass gasification with steam in a dual-fluidized bed gasifier (DFBG) was simulated with ASPEN Plus to investigate the amount of yield and composition of the syngas and the contents of tar and char are calculated as well. The H_2 concentration is higher than that of CO under the normal DFBG operation conditions, but they will change positions when the gasification temperature is too high above about 950°C, or the S/B ratio is too low under about 0.15. Tar content in the syngas can also be predicted using the model, which shows a decreasing trend of the tar with the gasification temperature and the S/B ratio.

Another DFBG modelled by Doherty et al. (2013) with using wood chip as feedstock by equilibrium model in ASPEN PLUS. The model is validated and syngas composition is predicted, heating value and CGE are found in very good agreement with published data. Gasification temperature, biomass moisture, S/B ratio, air-fuel (A/F) ratio and air and steam temperature are manipulated. As the obtained result shows, gasifier should be operated in the range 850-950 °C; biomass moisture content is the most significant parameter regarding CGE and should be as low as possible; S/B ratio is the most important parameter in terms of lower heating value (LHV) but is the least significant in respect of CGE; air-fuel ratio should be as low as possible while ensuring complete combustion; air preheating is more attractive than steam preheating.

Panda (2012) conducted research on process simulation of rice husk gasification using ASPEN PLUS with kinetic modelling. The effect of temperature, ER and S/B ratio on gasification of rice husk using an atmospheric fluidized bed gasifier have been investigated. The results show that the H_2 concentration in the product gas increases rapidly with increase in temperature (500-700^oC). Higher ER is not recommended for gasification as it results complete combustion of carbon present in the feed resulting higher percentage of CO_2 in the product gas. Also low ER (<0.2) is not preferred as it results pyrolysis rather than gasification. For the work of Panda (2012), the optimum ER lies between 0.20 and 0.24.

Bassyouni et al. (2014) has performed process simulation of biomass using downdraft fixed bed in ASPEN HYSYS. Gai et al. (2014) and Atnaw et al. (2013) had done experimental work using downdraft fixed bed to study the calorific value and HHV of syngas respectively. Chen et al. (2013) has studied fixed bed gasification using ASPEN

PLUS. Kinetic simulation was only done by Panda (2012) and Nikoo & Mahinpey (2008) using ASPEN PLUS. Obviously, from here it can be seen that ASPEN HYSYS is rarely used by researchers in modelling the gasification. Most of the journals' approach in simulating gasification process is equilibrium (Im-orb et al., 2016; Doherty et al., 2013; Chen et al., 2013 and Ramzan et al., 2011).

Recent works on biomass gasification has been summarised in Table 2-13. In addition, the selected models together with their study parameters, gasification types, description and assumptions are summarised in Table 2-14.

Table 2-13: Previous studies on biomass gasification.

Researcher	**Type of Gasifier**	**Research Approach**	**Simulator**
Im-orb et al. (2016)	Not specified.	Equilibrium	ASPEN PLUS
Gai et al. (2014)	Downdraft Fixed Bed	Experiment	-
Bassyouni et al. (2014)	Downdraft Fixed Bed	Equilibrium	ASPEN HYSYS
Atnaw et al. (2013)	Downdraft Fixed Bed	Experiment	-
Doherty et al. (2013)	Dual-Fluidised Bed	Equilibrium	ASPEN PLUS
Panda (2012)	Fluidised Bed	Kinetic	ASPEN PLUS
Chen et al. (2013)	Fixed Bed	Equilibrium	ASPEN PLUS
Loha et al. (2011)	Fluidised Bed	Experiment, Equilibrium	MODELING
Ramzan et al. (2011)	Not Specified	Equilibrium	ASPEN PLUS
Shen et al. (2008)	Fluidised Bed	Equilibrium	ASPEN PLUS
Nikoo & Mahinpey (2008)	Fluidised Bed	Kinetic	ASPEN PLUS
Mitta et al. (2006)	Fluidised Bed	Equilibrium	ASPEN PLUS
Zainal et al. (2001)	Downdraft Fixed Bed	Equilibrium	MODELING

Table 2-14: Previous literature work on biomass gasification’s process simulation.

Reference	**Parameters**	**Gasification Type**	**Description**	**Assumptions**
He et al. (2012)	1. Temperature 2. Steam to Biomass ratio 3. Biomass moisture content	Dual fluidised bed gasifier	• A DFBG consists of two beds. One is blown with steam to gasify biomass and to produce syngas. • RGibbs module is employed to perform calculation, according to the Gibbs free energy theory. • RStoic models drying stage, RYield models devolatilization, RGibbs models steam-reforming and also combustion stages. • Biomass moisture is taken into account.	• The process is at steady state. • The biomass feedstock and bed materials are fed at a uniform temperature. • The ash as well as bed materials are inert. • The char particles are spherical and of uniform size. • The mixing of solid particles is perfect. • The combustion and gasification of biomass are described by the shrinking core model.
Chen et al. (2013)	1. Temperature 2. Type of fixed bed gasifier 3. Fuel gas 4. Equivalent Air Ratio	Fixed bed	• ASPEN PLUS is utilized. • Based on minimization of the Gibbs free energy at equilibrium. • Considered four sections: drying, pyrolysis, gasification, and combustion.	• The residence time is long enough to allow the chemical reactions to reach an equilibrium state. • Char is assumed to contain only carbon as RGIBBS cannot handle char which is referred to as “non-conventional”.

Reference	Parameters	Gasification Type	Description	Assumptions
			• It resembles an updraft fixed bed without • injecting the flue gas (mainly CO2) from the combustor back into the gasifier. • The main reactors were simulated by three blocks in Aspen plus: RSTOIC, RYIELD and RGIBBS. • RSTOIC was used to simulate the drying process (moisture evaporated). • RYIELD was used to model pyrolysis process by specifying the yield distribution vector according to the MSW ultimate analysis, which was calculated using a FORTRAN program. • RGIBBS was used to predict the equilibrium composition of the syngas in the production.	• Gasification process begins with pyrolysis and continues with combustion. • Ambient temperature is taken 25^{o}C. • The solid residue from gasification section consisted of carbon and ash. • The characteristics of MSW was an average value of MSW from different provinces in China and the MSW feed rate was 1.0 kg/h.

Reference	Parameters	Gasification Type	Description	Assumptions
Doherty et al. (2013)	1. Temperature 2. Biomass moisture content 3. STBR 4. Air-fuel ratio	Dual Fluidised Bed	- ASPEN PLUS is utilized. - Peng-Robinson equation of state with Boston-Mathias modification was selected. - The biomass lower heating value (LHV) was also specified with the HCOALGEN and DCOALIGT property models chosen to estimate the biomass enthalpy of formation, specific heat capacity and density based on the ultimate and proximate analyses. - Equilibrium process simulation.	- Isothermal operation. - Steady state operation - Zero-dimensional - Atmospheric pressure (approximately 1 bar) - Ideal gases - Negligible pressure drops - Char is 100% carbon - All fuel bound N_2 is converted to NH_3. - All fuel bound sulphur (S) is converted to H_2S. - Drying and pyrolysis are instantaneous - Tar formation is not considered. - Heat loss from gasifier is neglected.
Nikoo & Mahinpey (2008)	1. Temperature 2. steam to biomass ratio	Fluidised Bed	- ASPEN PLUS is utilized, reaction kinetic-based. - Overall gasification process consists of decomposition of the feed, volatile	- Process is steady state and isothermal - Biomass devolatilization takes place instantaneously and volatile products

Reference	Parameters	Gasification Type	Description	Assumptions
			reactions, char gasification and gas-solid separation. • RYIELD was used to simulate the decomposition of the feed. • RGIBBS was used for volatile combustion, in assuming that volatile reactions follow the GIBBS equilibrium. • RCSTR performs char gasification by using reaction kinetics, written as an external FORTRAN code.	mainly consist of H_2, CO, CO_2, CH_4, and H_2O. • All the gases are uniformly distributed within the emulsion phase • Particles are spherical and of uniform size and the average diameter remains constant during the gasification, based on the shrinking core model. • Char only contains carbon and ash • Char gasification starts in the bed and completes in the freeboard.
Panda (2012)	1. Temperature 2. Steam to biomass ratio	Fluidised Bed	• ASPEN PLUS is utilized, reaction kinetic-based. • Fluidised-bed gasification. • Biomass particle decomposes quickly to form char, tar and gaseous products. • RYield was used to simulate the decomposition of the feed.	• The gasification process is isothermal and steady state. • Biomass de-volatilization is instantaneous in comparison to char gasification. • The biomass particles are spherical and are not affected in course of the reaction.

Reference	Parameters	Gasification Type	Description	Assumptions
			• RGibbs, was used for volatile reactions. • RCSTR performs char gasification by using reaction kinetics.	• All the gases are uniformly distributed within the emulsion phase. • Char consists of only carbon and ash. • Char gasification starts in the bed and ends in the freeboard.
Ramzan et al. (2011)	1. Temperature 2. Equivalence Ratio 3. Biomass Moisture Content 4. Steam Injection	Not specified.	• ASPEN PLUS is utilized, kinetic free equilibrium model based • At first stage, the moisture content of the fuel is decreased before feeding to the reactor. • At second stage, biomass is decomposed into volatile components and char, yield distribution is specified using FORTRAN statement. • At third stage, the partial oxidation and gasification reactions are modelled using Gibbs free energy.	• Steady state kinetic free model • Isothermal system • All sulphur goes to H_2S • Only NH_3 forms, no oxides of nitrogen are produced.

2.6.3 Co-gasification using Biomass & Coal

Co-gasification is defined as gasification of a mixture of waste/biomass and coal which offers several opportunities, especially to utility companies and customers, to protect the environment by reducing Green House Gases (GHG) emissions from existing process equipment. It creates opportunities in industries such as forestry, agriculture, and food processing to manage large quantities of combustible agricultural and wood wastes (Farzad et al., 2016). The significance and impact of co-gasification have been investigated for the cause of clean coal technology. In recent years, there has been significant research interest in co-gasification due to environmental and technical benefits of various biomass and coal mixtures such as Japanese cedar (Cryptomeria japonica) wood and coal (Kumabe et al. 2007), coal and saw dust (Vélez et al. 2009), coal and pine chips (Pan et al. 2000).

Yuehong et al. (2006) reported a new co-gasification technology and a conceptually designed gasifier for such technology are proposed and modelled using the ASPEN PLUS process simulator. The simulation results are in good agreement with the laboratory scale experimental data at 1273K which is useful for further analysis. It is reported that oxygen has a certain effect on the syngas composition and reactor temperature, and an optimum range of O_2/fuel ratios exists where the concentrations of H_2 and CO show maximum values and the natural gas is completely converted at an appropriate reactor temperature. The increase of steam flow rate results in a moderate reduction of the concentrations of H_2 and CO, as well as the reactor temperature.

Pinto et al. (2003) has conducted experiment to investigate the effect of gasification medium, which consist of air, steam or a mixture of both, and temperature on syngas composition in fluidised bed. The utilised feedstocks are coal, pine and polyethylene (PE) waste. As the result, the presence of air shows disadvantages, as it reduces the HHV of the syngas, due to N_2 diluting effect. The increase of steam flowrate has proven to be advantageous, because reforming reactions were favoured, thus hydrocarbons concentrations decreased and H_2 release increased.

Goyal et al. (2010) discussed the modelling and simulation of a fluidized bed coal gasifier which uses a mixture of coal and petcoke as its feed. It has been found that increase of petcoke content in the feed mixture tends to reduce the efficiency and carbon conversion but increases the amount of syngas produced. It has also been found that increase in ash content of coal decreases the carbon conversion.

Adeyemi and Janajreh (2014) investigated entrained flow gasification (EFG) of Kentucky coal and wood waste using detailed kinetics-based ASPEN Plus model and experimental diagnostics. The constructed model results suggest that increasing the diameter and height of the gasifier is directly proportional to more production of CO and H_2. The model also predicted lower mole fraction of the CO and H_2 for the waste wood compared to the Kentucky coal, as wood has a higher oxygen content (43.62%) and lower carbon content (49.41%).

Jang et al. (2015) suggested to modify the feedstock by using hybrid coal, which is manufactured from KIDECO raw coal and biomass-derived carbon through the method of coating. The co-gasification system is constructed using RGIBBS in ASPEN PLUS to investigate the composition of syngas in comparison with pure coal and pure biomass. From the sensitivity analysis, the water content of the slurry causes only a slight change in the yield of synthesis gas. Also the reactor temperature and pressure have little effect on the yield of synthesis gas in the model.

Kuo & Wu (2015) attempted to design co-gasification process in equilibrium state using RGibbs model block in Aspen Plus with investigating the effect of co-gasification of coal/torrefied biomass blends of 0, 20, 40, 60, 80, 100% w/w torrefied biomass content. It is reported that different BR ratio has an optimal S/F ratio.

Co-gasification process simulation has been done by Yuehong et al. (2006) in designing new conceptual gasifier using ASPEN PLUS, Adeyemi & Janajreh (2015) in modelling kinetic entrained flow bed using ASPEN PLUS, Jang et al. (2015) in simulating equilibrium entrained flow gasification using ASPEN PLUS and Kuo & Wu (2015) in investigating influence of B/C ratio in co-gasification process. It can be seen that there is zero or limited work of process simulation in co-gasification process using ASPEN HYSYS as the process simulator. Adeyemi & Janajreh (2015) and Jang et al. (2015) had done research on entrained flow gasifier however it is limited to ASPEN PLUS only.

Table 2-15 shows previous research works on co-gasification system with using biomass and coal as feedstocks. Table 2-16 shows the process description and assumptions made for literature co-gasification system.

Table 2-15: Previous studies on biomass and coal co-gasification.

Researcher	**Type of Gasifier**	**Research Approach**	**Simulator**
Adeyemi & Janajreh (2015)	Entrained Flow Bed	Kinetic	ASPEN PLUS
Jang et al. (2015)	Entrained Flow Bed	Equilibrium	ASPEN PLUS
Kuo & Wu (2015)	Not specified	Equilibrium	ASPEN PLUS
Goyal et al. (2010)	Fluidised Bed	Modelling	-
Yuehong et al. (2006)	Not Specified	Equilibrium	ASPEN PLUS
Pinto et al. (2003)	Fluidised Bed	Experiment	-

Table 2-16: Previous literature work on co-gasification's process simulation.

Reference	Feedstock	Gasification Type	Description	Assumptions
Adeyemi & Janajreh (2015)	1. Gasifier Diameter 2. Gasifier Height 3. Fuel Type	Entrained-Flow	• ASPEN PLUS is utilized, kinetic-based model. • Redlich-Kwong-Soave property method was used to calculate the physical properties of mixed conventional components and the conventional inert solids. • HCOALGEN and DCOALIGT build in models were used to calculate the enthalpy and density of non-conventional components respectively. • At first stage, drying, the moisture release process was modelled with the RStoic block labelled as DRYER followed with a secondary separation block Flash2 labelled as FLASH-A. Using RStoic block and built in FORTRAN code, approximately 95% of the moisture content is removed.	• Devolatilization process can be assumed to be instantaneous. • Only four of the released volatile components, namely CO, H_2, CH_4 and benzene, can undergo combustion. • The gasification model is attaining steady state of thermochemical conversion • The gas phase is assumed to be instantaneously and perfectly mixed with the solid phase • The pressure drop in the gasifier is neglected • The particles are assumed to be spherical and of uniform size • The ash layer formed remains on the particle during the

Reference	Feedstock	Gasification Type	Description	Assumptions
			Subsequently, the Flash2 separator was used to remove the vapour from other components of the fuel. • Second stage, devolatilization was modelled with the RYield reactor labelled as YIELD-A, a mixer labelled as MIX, a separator labelled as SEP-B and an RGibbs reactor labelled as GIBBS. The YIELD-A reactor breaks down the fuel into char and elements consisting of carbon, hydrogen, nitrogen, oxygen and sulfur. The RGIBBS reactor utilizes the Gibbs minimization method to find the equilibrium composition of the volatiles which were identified as argon, CO, H_2, CO_2, vapor, H_2S, N_2, CH_4 and benzene. • Four reactions were modelled in ASPEN Plus with an RStoic reactor labelled COMBUST.	reactions based on the unreacted-core shrinking model • The temperature inside the particle is assumed to be uniform • The char gasification process starts at the heating region near 0.5 m from the top

Reference	Feedstock	Gasification Type	Description	Assumptions
Robinson & Luyben (2008)	1. Coal Type	Fluidised Bed	• ASPEN PLUS is utilized, equilibrium model in dynamic. • To have a gasifier model in Aspen Plus that can be exported to Aspen Dynamics. Kinetic reactor in ASPEN PLUS	• Assumes chemical equilibrium based on Gibbs free energy minimization. • A rigorous high-fidelity dynamic model of the gasifier is not considered. • Whole system gas-phase. • Large vessel, throughputs are large. • Residences times in entrained flow gasifier are in order of 10s to 20s.
Jang et al. (2015)	1. Slurry water content 2. Oxygen ratio	Entrained Flow	• ASPEN PLUS is utilized, equilibrium model. • The Gibbs function can be adopted as an equilibrium model for the devolatilization phenomenon from coal as $\Delta G = 0$.	• Steady-state equilibrium model.

Reference	Feedstock	Gasification Type	Description	Assumptions
	3. Operating temperature 4. Operating pressure			
Kuo & Wu (2015)	1. Steam to fuel ratio 2. Biomass ratio	Not specified.	• ASPEN PLUS is utilized, equilibrium model. • After drying, the fuels are decomposed into its elemental constituents in the block RYield • The co-gasification is simulated by a block called RGibbs, in which the chemical equilibrium calculations are performed by minimizing the Gibbs free energy.	• Equilibrium steady state model.

It is obvious that most of the previous studies revolving around the studies of fluidised bed and fixed bed with using ASPEN PLUS as the simulator. ASPEN PLUS is commonly used in coal and biomass conversion processes. The reason is that it has inbuilt library models for solid properties calculations and uses FORTRAN code as customary language for numerical calculations (Bassyouni et al., 2014). However, in fact, there are limited researches conducted on the co-gasification of biomass and coal, and there is an apparent lack of fundamental understanding of the interactive effects of coal and biomass during the co-gasification (Xu, 2013). In addition, there is no comprehensive mathematical model available in the literature on co-gasification. The use of raw EFB and coal in co-gasification is even less extensively studied.

Most of the journals' approach in simulating gasification process is equilibrium (Im-orb et al., 2016; Doherty et al., 2013; Chen et al., 2013 and Ramzan et al., 2011).Adeyemi & Janajreh (2015) and Jang et al. (2015) had done research on entrained flow gasifier however it is limited to ASPEN PLUS only.

Hence, based on the current works, it can be seen that the findings are very positive and the work on entrained-flow co-gasification using EFB & coal is limited, which driven the motivation of this research project. Most of the literature focused on downdraft gasification. Only a few literatures that employs kinetic modelling approach in process simulation of gasification. Therefore, the objective of present work is meaningful, which is to develop a process simulation of co-gasification system using biomass (raw EFB) and coal (Adaro Coal) as the feedstock. Besides, the influence of parameters consisting of ER, temperature, S/B ratio and B/C ratio in co-gasifier on the composition of producer gas will be investigated from the process simulation.

CHAPTER 3

METHODS & THEORY

3.1 Methods

For analysing the production of syngas from co-gasification using EFB and ADARO coal as combined feedstock, specialized software Aspen HYSYS (Aspen Technology Inc., 2003) flowsheet simulations were made and used for optimisation purposes. Process simulation of co-gasification in this research work will be categorised into stages in order to get accurate and precise result. The methods employed in running simulation will based on imitation and modification approach.

First stage of performing process simulation of co-gasification is to refer and compare with the past literature work in gasification and co-gasification. This stage carries the objective to investigate the precision and to give first understanding on the procedure of process simulation. At first stage, through the comparison of process simulation on previous research work will help in determining the quantity and types of reactors required. The necessity and importance for each reactor and unit operation will be studied based on its justification.

In second stage, process simulation of co-gasification will be modified based on the previous research works. At this stage, type of reactors and unit operations will be replaced with alternatives to investigate the effect of changes. Various types of units will be studied using the provided selections in ASPEN HYSYS. At second stage, raw materials and productions will be varied according to desired objectives of this research work. This modification with using alternatives will enhance the level of understanding for each process and its respective objectives. Reasoning and justification will be constructed to figure out the theories.

In third stage, a whole new process simulation with taking previous work as reference will be constructed with using the raw material of empty fruit bunch together with coal to undergo the process of co-gasification using entrained flow gasifier concept. Number of reactors and unit operations are assumed to be likely the same as previous work. However, type of reactors and involved units will be detailed with design and calculation to ensure the feasibility and accuracy in result. The process simulation result is discussed thoroughly in the form of case study. Several case studies will be constructed and compared finely in order to obtain the optimum process operation method. In final stage, the simulated results of co-gasification are validated through the comparison with the data obtained from the referred literature. The model predictions are expected to exhibition high endorsement with the current data based on the data analysis. The obtained result is expected to be useful in future design, operation, optimisation and control of the co-gasification process in the entrained flow system which help to achieve the objective in countering energy supply.

3.2 Theory

The effect of the feedstock with a varying content of EFB biomass and coal on the co-gasification behaviour will be investigated by varying the biomass ratio from 0 (B0) to 1 (B100), based on the EFB biomass content in the total feedstock on a carbon basis. The coal is Adaro coal which obtained from Adaro, Indonesia. The specification of EFB biomass will be based on the by-product production from crude palm oil in Malaysia. The process simulation is conducted to get the production gas or synthesis gas, expecting with a high content of H_2 gas. The gasifying agent used for reforming and raw materials burning are the steam and air with fixed amount of oxygen. The production gas must be optimum and match the demand for certain end uses with minimum consumption of coal and agents of reforming and burning, and to reduce the environmental footprint.

3.3 Assumptions

In the process simulation of co-gasification, a few assumptions have been safely drafted, which will simplify the process without sacrificing too much accuracy and precision. These assumptions are likely obtained from previous research works as they are safe to ease the process simulation, as numbered as following.

1. Only main and important reactions will be considered in performing simulation of gasification and co-gasification, which have been stated in Table 3-1.

Table 3-1: Major gasification reactions (Bassyouni et al., 2014).

Name of Reaction	**Reaction**	**Heat of Reaction at 25ºC (kJ/mol)**	**Equation**
Complete Combustion	$C + O_2 \rightarrow CO_2$	-394	2.1
Incomplete Oxidation	$C + \frac{1}{2}O_2 \rightarrow CO$	-283	2.2
Water-Gas	$C + H_2O \rightarrow CO + H_2$	+131	2.3
Boudouard	$C + CO_2 \rightarrow 2CO$	+172	2.4
Hydrogasification (Methanation)	$C + 2H_2 \rightarrow CH_4$	-74.8	2.5
Water-Gas Shift	$CO + H_2O \rightarrow CO_2 + H_2$	-41.2	2.6
Ammonia Formation	$N_2 + 3H_2 \rightarrow 2NH_3$	-46.1	2.7
Hydrogen Sulphide Formation	$S + H_2 \rightarrow H_2S$	-21	2.8

2. Steady state isothermal process, which mean the process conditions in all unit operations remain constant as time changes.
3. Devolatilisation happens instantaneously after introducing biomass (EFB) into the co-gasifier and volatile products mainly consist of H_2, CO, CO_2, CH_4 and H_2O are considered (Nikoo & Mahinpey, 2008).
4. Feed particles are uniformly sized with spherical shape.
5. The whole amount of sulphur in biomass EFB reacts to form H2S only, due to the low content of sulphur in the fuel (Schuster, 2000).
6. Only NH_3 is formed from the nitrogen element in EFB during co-gasification, as the inaccuracy of this simplification is negligible (Schuster, 2000).
7. Char is modelled to contain 100% carbon only (Bassyouni et al., 2014).
8. Tar and higher hydrocarbons are negligible (Im-orb et al., 2016).

9. The ash is considered as the mixture of inorganic components, modelled to be a non-reactive inert (Im-orb et al., 2016).

3.4 Process Simulation Description

There are four important stages to consider in gasification and co-gasification, consisting of decomposition of the feed (devolatilisation), volatile reactions, char gasification and gas-solid separation. Each of the stages are represented by a model block in ASPEN HYSYS. Figure 3-1 shows a general idea of co-gasification process in process simulation.

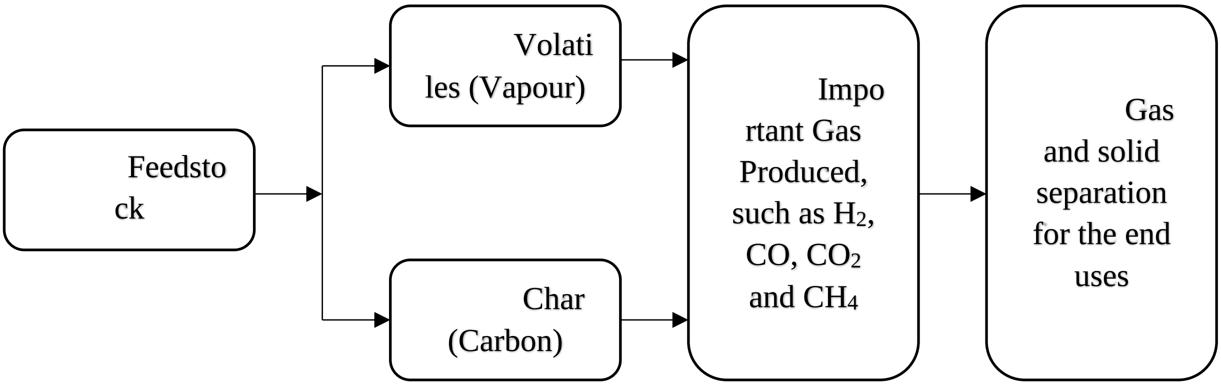

Figure 3-1: General idea of co-gasification of using EFB and Coal as feedstock in process simulation.

In HYSYS simulation, it is firstly to define a new component list which comprises of CH_4, H_2O, CO, CO_2, H_2, N_2 and O_2 as the main products. Peng-Robinson (PR) equation of state and equilibrium is then chosen for the fluid package, since most of the chemical components are non-polar and in real gas. The pressure for all unit operations are set at 1 bar, temperature is set increasingly from initial until the last reactor according to the concept of gasification.

The simulation is performed once all the manipulated variables, i.e. temperature, ratio of feedstock and pressure have been set within the reactors system. The analysis result obtained from the simulation based on the thermodynamics and kinetic reactions in the bank of ASPEN HYSYS will be recorded and compared with the case study created from previous research works. The deviation and graph trends are justified based on the comparisons. Few case studies will be generated in order to study and discuss the result of co-gasification process simulation. The process simulation will be a plenty of trials and errors in order to ensure accuracy in process prediction.

In this simulation, energy requirements of the fuel preparation, drying and feeding equipment are not taken into account (Ersoz et al., 2006). In the first stage of co-gasification, the feed consists of EFB and Adaro Coal, in the ratio from 0.5 to 3. The co-gasifier model of this study is an entrained flow gasifier. To model an entrained flow co-gasifier using ASPEN HYSYS, the overall process is broken down into a number of sub-processes, which are equivalent to the mentioned zones. It is modeller’s decision to choose to model each of these zones separately or combine them in one unit.

For the comparison of process simulation model, literature work by Bassyouni et al. (2014) is taken as reference for comparison study. Figure 3-2 shows the process simulation of biomass gasification with using Date Palm Leave (DPL) as feedstock. The process is simulated with categorising the downdraft gasification into three main stages, consisting of biomass decomposition, volatiles combustion and char gasification with description of main unit operation models in Table 3-1. The detailed process description is explained in the following sub-sections.

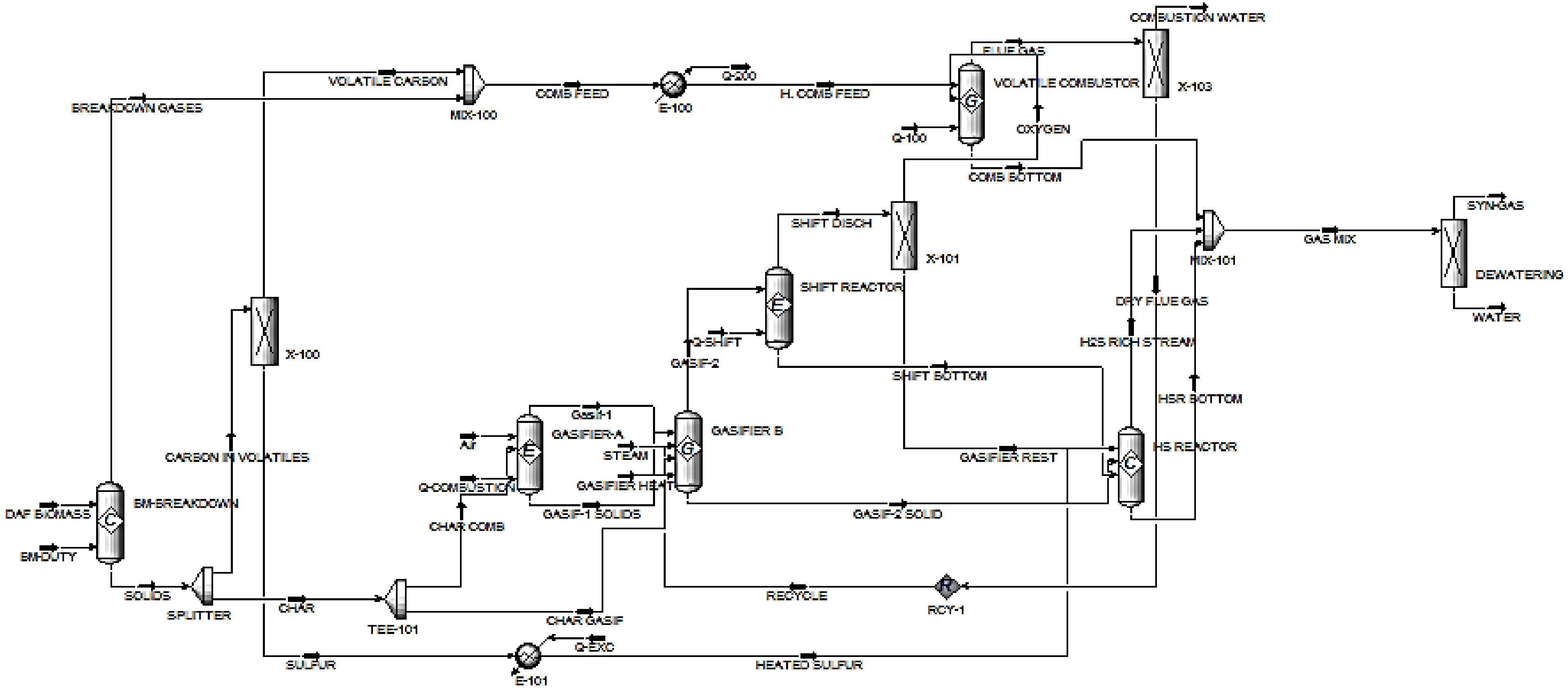

Figure 3-2: Process simulation of biomass gasification with feedstock of DPL.

3.4.1 Fluid Package

Peng-Robinson has been selected as the fluid package for the process simulation of gasification and co-gasification.

3.4.2 Decomposition of Biomass

At this process stage, a conversion model block is used in HYSYS. With referring to Figure 3-2, BM Breakdown simulates the pyrolysis process of biomass which closely represents the decomposition process in a downdraft gasifier in terms of its functionality. In HYSYS, the biomass is defined as a hypothetical component. The molecular weight and atomic composition of DPL are obtained from the Proximate Analysis (PA) and Ultimate Analysis (UA) data from the literature work by Bassyouni et al., 2014 (see Table 3-2). Biomass in this simulation is assumed to contain only fixed carbon and volatile matter, as the ash-free model is hypothesised. Drying process is not taken into account in this process simulation. At BM Breakdown, the biomass is split into its constituent conventional components of C, N_2, H_2, O_2 and S, based on its experimental UA. The char is assumed to be 100% carbon (graphite) (Doherty, 2009). The streams Comb Feed and Char in the simulation represent volatile matter and fixed carbon respectively, defined in accordance with the PA of DPL (see Table 3-2).

Table 3-2: Characteristics of biomass and coal in this research study.

	DPL (Bassyouni et al., 2014)	**Raw EFB**	**Adaro Coal E4000 (www.adaro.com)**
Proximate Analysis			
Moisture Content (MC)	5.0	5.977	21
Volatile Matter (VM)	78.1	68.94	40
Fixed Carbon (FC)	5.2	5.893	36
Ash	11.7	20.48	3
Ultimate Analysis			
C (%)	49.4	43.518	72
H (%)	5.8	7.255	5
N (%)	1.2	3.041	0.9
S (%)	1.3	0.290	0.3
O (%)	42.3	45.896	21.8
DPL Density (kg/m^3)	298	1364.7	1800 (assumed)

3.4.3 Volatiles Combustion

Assuming combustion of VM follows Gibbs equilibrium, volatiles combustion is modelled with a Gibbs reactor in ASPEN HYSYS, named Volatile Combustor. The streams of Carbon in Volatiles and Breakdown Gases are mixed in MIX-100 to be Comb Feed. The stream is heated up at E-100 to be H. Comb Feed which contains a small amount of carbon, representing gaseous carbon in VM. Carbon in H. Comb Feed can be calculated by the difference method using PA data. The modelling of VM combustion is performed in accordance with the hydrodynamics of downdraft gasifier. The small diffusional effects of synthesis gas in upper zones have been accommodated in the simulation by the Oxygen stream leaving splitter X-101. The combustion products (CO and H_2O) of VM have their share in the gasification reactions. The Flue Gas stream from Volatile Combustor in the simulation is recycled to the Gasifier-B using recycle operation RCY-1.

3.4.4 Char Gasification

The gasification process in this simulation is modelled as a set of equilibrium and Gibbs reactors in ASPEN HYSYS, modelling various zones of gasifier which are characterised by each of the reactions. The major gasification reactions, stated in Table 3-1 were defined as a total of six equilibrium reactions in HYSYS simulation Basis Manager, specifying the variation of the equilibrium constant of each reaction with respect to temperature (Lee et al., 2014).

Gasifier-A is an equilibrium reactor which models the char combustion reaction in the air so that the exiting streams, Gasif-1 and Gasif-1 Solids are in both chemical and physical equilibrium. Char Comb stream enter along with air into Gasifier-A. The reactions which expected to occur at this model block are complete combustion (eqn. 2.1) and incomplete oxidation (eqn. 2.2). Gasifier-A closely models the combustion zone of a gasifier.

Both the exiting streams from Gasifier-A, together with Steam stream enter Gasifier-B, which models water-gas (eqn. 2.3), boudouard (eqn. 2.4) and hydrogasification (eqn. 2.5). Gasifier-B is a Gibbs reactor that models the reactions using Gibbs free energy minimization method at equilibrium. CO Shift Reactor is an equilibrium reactor which models water gas shift (WGS) reactor to complete the gasification process. Both Gasifier-B and CO Shift Reactor collectively simulate the gasification zone of the gasifier.

The entire synthesis gas stream goes through HS Reactor which models the conversion of solid sulphur into H_2S with assuming a conversion factor of 100% using a conversion model block. The exit streams from HS Reactor and Volatile Combustor merge at MIX-101, giving the name of Gas Mix as output stream. The exit stream contains moisture which is to be separated at Dewatering splitter unit, which is equivalent to the knockout drum downstream the gasifier. Syn-Gas stream represents the dry synthesis gas which obtained from the gasification of biomass.

3.4.5 Technical Challenges of Co-gasification

Undoubtedly, thermal gasification is one of the most promising technologies for large-scale commercial plants. Co-gasification with coal will achieve potential benefits of biomass and bio-solid wastes by overcoming the problem of low density of biomass (Oakey et al., 2016). This directly will make the commercial production of gaseous fuel with using biomass as one of the feedstocks economically viable. However, there are some technical challenges also for using both coal and biomass together in a reactor. The first technical challenge of co-gasification is the gas cleaning technique in removing tars and other impurities, consisting of NH_3, H_2S and HCl based on the solid fuel nature (Oakey et al., 2016). When solid wastes are added into solid fuel, ash separation and treatment are taken into account to solve the gas cleaning problem. This can be overcome by designing treatment unit operation using experimental data. Hence, it is not a concern in this process simulation.

Another major challenge is that coal and biomass have different density and material handling properties which cause segregation inside the gasifier if gasify them in the same reactor (Brar et al., 2013). Moreover, the different gasification rates of coal and biomass also create problems with unburnt carbons due to the difference in carbon conversion efficiency. This is because of the differences in density, shape, and size of the coal and biomass particles cause segregation during transport of the mixture and as it is processed inside the gasifier (Brar et al., 2013). Co-gasification requires preconditioned, uniform mixtures of coal and biomass feedstock (Kumabe et al. 2007). In addition, different material handling properties of coal and biomass also cause problems for the simultaneous gasification.

Hence the feeding options of co-gasification system plays an important role to overcome the efficiency challenge. There are a few options in feeding the coal and biomass to the gasifier. Table 3-3 shows feeding options of co-gasification with their respective advantages and disadvantages.

Table 3-3: Several possible feeding option in co-gasification system and their pros and cons (Brar et al., 2013).

Feeding Option	Advantages	Disadvantages
Perform gasification separately and mix product gas streams	Able to effectively gasify both coal and biomass separately and maintain high carbon conversion rate.	Costly as two different systems are required.
Feed coal and biomass into different streams into the same gasifier	Cheaper than feeding them separately.	Segregation of feed in gasifier might occur as coal and biomass hold different gasification and combustion behaviour.
Blend coal and biomass into a homogenous mixture and feed through a single feed stream	Able to homogenise the mixture with combined properties.	Segregation of feed in gasifier might occur as coal and biomass hold different gasification and combustion behaviour.
Co-process coal and biomass to minimize the segregation and tar formation.	Effective handling method to save cost.	Experimental data is required for co-process solid fuel. Gasification behaviour needs be identified and modification of existing equipment and/or its operation is required.

Based on Table 3-3, it can be seen that by performing gasification separately and mix product gas streams is the best feeding option to be chosen for this research work as the carbon conversion rate will be higher. The data obtained from this option can be further analysed for other feeding options through experimental work. Hence, two different systems of gasification will be constructed and the syngas streams from each will merge into one at the final mixer.

The co-gasification system in this research work employs the concept of retrofitting the biomass gasification system by adding in the coal gasification system. The co-gasification system in this work is represented by two similar process with different feedstock for each.

3.4.6 Co-gasification Process Simulation

In co-gasification, the process is modelled by combining the gasification of biomass and gasification of coal at the stream of syngas through the concept of process retrofit. The model blocks used for biomass gasification are utilised to simulate the gasification of coal as well. At this stage, the feedstock of biomass is changed from using DPL to raw EFB, while for the system of coal gasification, the feed is Adaro coal E4000. The Syn-gas from biomass gasification and Syn-gas-2 from coal gasification merge at Co-gasif Mix. Table 3-4 and Table 3-5 show the description of reactors in the simulation of using biomass and coal as feedstock respectively. Figure 3-3 shows the process simulation of co-gasification with using EFB and Adaro coal as feedstocks.

Table 3-4: Reactor blocks description utilised in the simulation of biomass gasification using ASPEN HYSYS.

Reactor	HYSYS Reactors Family	Reaction Zone	Description
BM Breakdown	Decomposition (Pyrolysis)	Conversion	This reactor models the decomposition of biomass (a hypothetical component) into conventional constituent components, assuming 100% conversion.
Volatile Combustor	Combustion	Gibbs	This reactor models the combustion of char generated during the pyrolysis of biomass using Gibbs free energy minimization approach.
Gasifier-A	Combustion	Equilibrium	This reactor models the biomass char combustion and incomplete oxidation process based on the equilibrium data.
Gasifier-B	Gasification	Gibbs	This reactor models the main gasification reactions by multiphase chemical and phase equilibrium calculations using Gibbs free energy minimization approach.
CO Shift Reactor	Gasification	Equilibrium	This reactor models the water gas shift (WGS) reaction to complete the gasification process.
HS Reactor	Gasification	Conversion	This reactor models the conversion of sulphur into H_2S, with assumption of 100% conversion.

Table 3-5: Reactor blocks description utilised in the simulation of coal gasification using ASPEN HYSYS.

Reactor	**HYSYS Reactors Family**	**Reaction Zone**	**Description**
BM Breakdown-2	Decomposition (Pyrolysis)	Conversion	This reactor models the decomposition of coal (a hypothetical component) into conventional constituent components, assuming 100% conversion.
Volatile Combustor-2	Combustion	Gibbs	This reactor models the combustion of char generated during the pyrolysis of coal using Gibbs free energy minimization approach.
Gasifier-A-2	Combustion	Equilibrium	This reactor models the charcoal combustion and incomplete oxidation process based on the equilibrium data.
Gasifier-B-2	Gasification	Gibbs	This reactor models the main gasification reactions of coal by multiphase chemical and phase equilibrium calculations using Gibbs free energy minimization approach.
CO Shift Reactor-2	Gasification	Equilibrium	This reactor models the water gas shift (WGS) reaction to complete the gasification process.
HS Reactor-2	Gasification	Conversion	This reactor models the conversion of sulphur into H_2S, with assumption of 100% conversion.

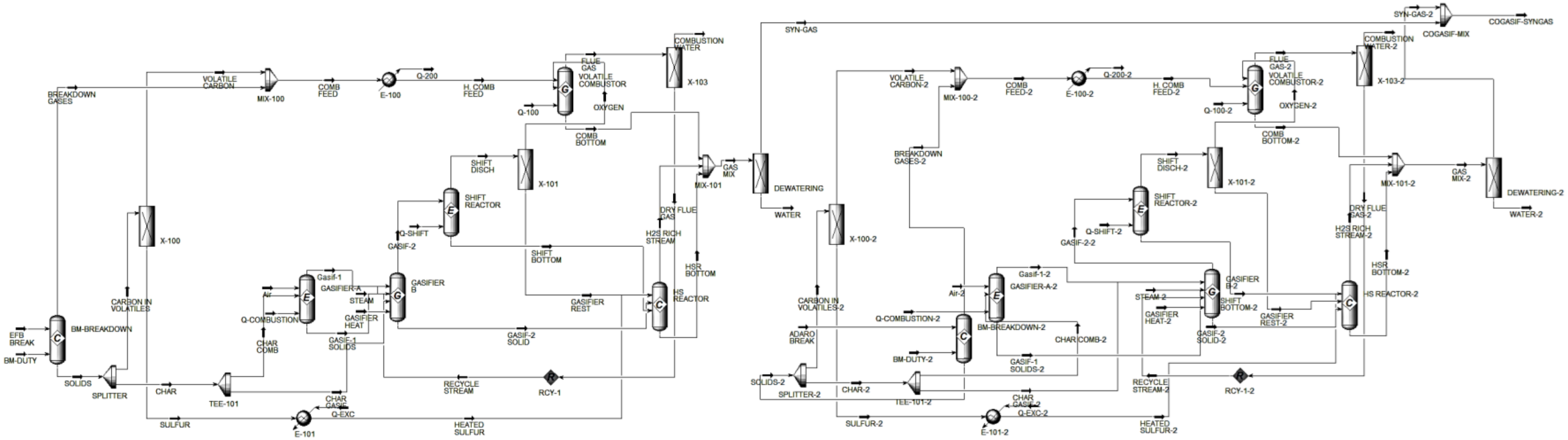

Figure 3-3: Process simulation of co-gasification with using raw EFB as biomass and Adaro Coal as coal feedstocks.

3.5 Model Comparison

The simulation results have been compared with the literature data of DPL gasification. The accuracy of the simulation results is estimated using the visual comparison between simulation of literature and current work, with comparing the composition of syngas constituent (H_2, CO, CO_2 or CH_4) using parameter of temperature. The equivalence ratio (ER) is not stated in the literature work, hence the value is predicted to be 0.3. All mathematical calculations were performed using Microsoft Excel. As shown, CO and CO_2 show the lowest and highest deviation respectively. The deviation of predicted composition of syngas from the literature data is due to the adjustment and assumptions made to complete the data of process simulation that is not given in the literature. The assumptions made were stated in Table 3-6. The visual comparison of result from Bassyouni et al. (2014) and current work result of process simulation using DPL is illustrated in Figure 3-4. The comparison shows fair agreement in terms of composition trend along the changes of temperature. The low production of methane gas is most probably due to the software replaces methane for every possible hydrocarbon reaction, as methane is the only hydrocarbon assumed in this simulation.

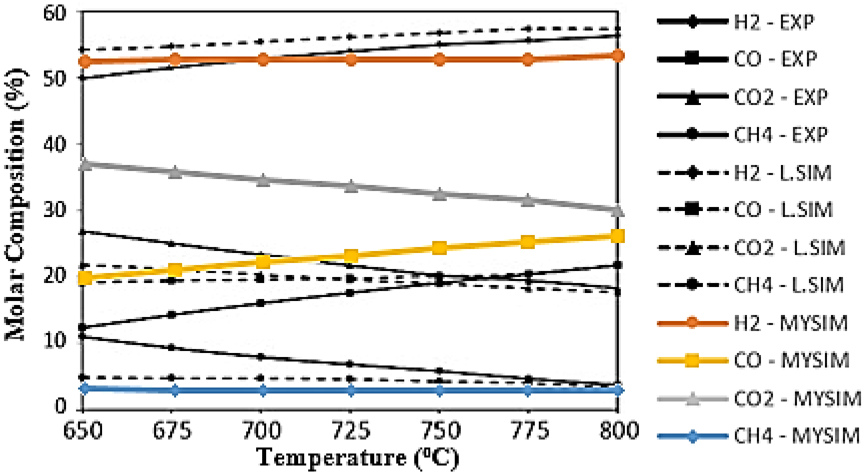

Figure 3-4: The comparison between work of Bassyouni et al. (2014) and current work in terms of change in molar composition of syngas against temperature.

Table 3-6: The comparison of input data between Mysim and Litsim and assumptions made.

Block Model	**Block Model Name**	**Parameters**	**DPL (Bassyouni)**	**DPL (My Simulation)**	**Remark**
Conversion	BM Breakdown	Temperature (^oC)	Unknown	300	Pyrolysis only produces constituting components, i.e. C, H_2, N_2, O_2 and S (from Amndine & Bour 2016, Master's thesis).
		Pressure (kPa)	Unknown	101.325	
		Flowrate (kg/h)	8	8	
Tee	Splitter	Ratio	Unknown	Carbon in Volatile and Char ratio is 9:1	Assumption.
Tee	TEE-101	Ratio	Unknown	Char Comb and Char Gasif ratio is 1:9	Assumption.
Splitter	X-100	Temperature (^oC)	Unknown	300	Assumption.
		Pressure (kPa)	Unknown	101.325	Assumption.
Equilibrium	Gasifier-A	Temperature (^oC)	800	800	
Data retrieved from Handbook of Alternative Fuel Technologies		Pressure (kPa)	Unknown	101.325	Assumption.
		Air Flowrate	Unknown	Taking ER = 0.3 (as optimum air flow rate)	Air flowrate based on ER. In stoichiometry, 1 mol of C reacts with 4.762mol of Air for complete combustion to produce CO.
Splitter	X-101	Temperature (^oC)	Unknown	800	

Block Model	Block Model Name	Parameters	DPL (Bassyouni)	DPL (My Simulation)	Remark
		Pressure (kPa)	Unknown	101.3	
Equilibrium	CO Shift Reactor	Temperature (^{o}C)	Unknown	800	
		Pressure (kPa)	Unknown	101.3	
Gibbs Reactor	Gasifier-B	Temperature (^{o}C)	800	800	
	(GIBBS)	Pressure (kPa)	Unknown	101.3	
Gibbs Reactor	Volatile Combustor	Temperature (^{o}C)	Unknown	800	
	(GIBBS)	Pressure (kPa)	Unknown	101.3	
Splitter	X-103	Temperature (^{o}C)	Unknown	800	
	(SPLITTER)	Pressure (kPa)	Unknown	101.3	
		Flowrate (kg/h)	Unknown	No water flowrate (top)	
Conversion	HS Reactor	Temperature (^{o}C)	Unknown	865.4	
	(CONVERSION)	Pressure (kPa)	Unknown	101.3	
Splitter	Dewatering	Temperature (^{o}C)	Unknown	865.3	
	(SPLITTER)	Pressure (kPa)	Unknown	101.3	

CHAPTER 4

RESULT & DISCUSSION

The steady state simulation developed is tested for its accuracy by simulating variation of synthesis gas composition with ER, temperature, S/B ratio and B/C ratio on ASPEN HYSYS. The feedstock in this simulation consist of raw EFB and Adaro Coal.

4.1 Effect of Equivalence Ratio

As biomass is a mixture of carbon and the other elements, hence the amount of air is the one of the important parameters in varying the composition of syngas. In this simulation, the air inlet stream is only at Gasifier-A, which models complete combustion and incomplete oxidation of biomass or coal. In stoichiometry, 1 mole of carbon requires 1 mole of O_2 and 0.5 mole of O_2 for complete combustion and incomplete oxidation respectively. Assuming air inlet consists of 0.79 mole of N_2 and 0.21 mole of O_2, the amount of air required for the reactions to occur is different from each type of biomass. The reason is every biomass has different composition of C, N, H, O and S elements. Equivalence ratio (ER) is defined as, for any process including pyrolysis of biomass or coal, the ratio of actual air fuel ratio over the stoichiometric air fuel ratio for complete combustion. The equation is stated as below.

$\mathrm{ER} = \frac{air_{actual}/fuel_{actual}}{air_{stoich}/fuel_{stoich}}$, where stoich refers amount required for complete combustion

The effect of ER has been studied using ASPEN HYSYS and the simulation results were analysed, shown in Figure 4-1. Saturated steam at 101.3 kPa is applied and S/B ratio of 1.5 at gasifier temperature of 1200^{o}C. The B/C ratio is 1, which is equivalent to B(50). As it is shown in Figure 4-1, the concentration of H_2 and CO drop with the increase of ER.

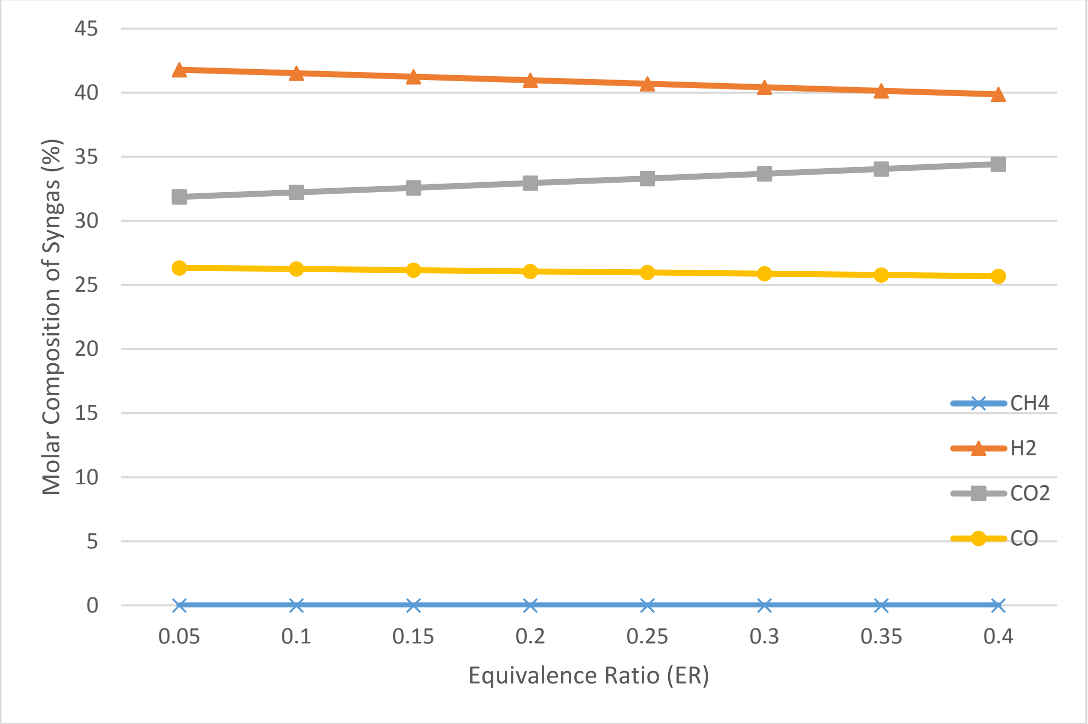

Figure 4-1: Effect of ER on molar composition of syngas in the Cogasif-syngas stream (T: 1200°C; B/C: 1; S/B: 1.5).

The concentration of CH_4 is negligible as the temperature is 1200°C, which unfavour the formation of CH_4. The reason is the production of CH_4 is mainly from Eqn. 2.5, an exothermic reaction, where the higher the temperature will shift the equilibrium backwards (Bassyouni et al., 2014). The concentration of CO_2 increases with the increase of ER. Similar trend reported in Begum et al. (2013). In the water-gas reaction (Eqn. 2.3), C reacts with steam and produces the syngas components: CO and H_2. Sequentially, the CO shift reaction (Eqn. 2.6) produces CO_2 and H_2 reacting with H_2O and CO.

Figure 4-2 shows the HHV of syngas and its H_2/CO ratio with the influence of ER. HHV depends on a large number of parameters but is strongly influenced by the amount of CO, CH_4 and H_2 in syngas (Ramzan et al., 2011). The syngas HHV and H_2/CO ratio drops with the increase of ER due to the formation of CO_2 in Eqn. 2.1. The HHV is found to be high for low ER due to the high CH_4 content (Doherty et al., 2009). The increase of air flow rate will favour the complete oxidation of carbon based on the nature of equilibrium constants of Eqn. 2.1 and Eqn. 2.2 (Chen et al., 2013). According to Wang et al. (2008), it suggests that the increase of ER will decrease the HHV of syngas due to low concentrations of H_2 and CO with high CO_2 content in the product gas, which is in good agreement with the current simulation work result.

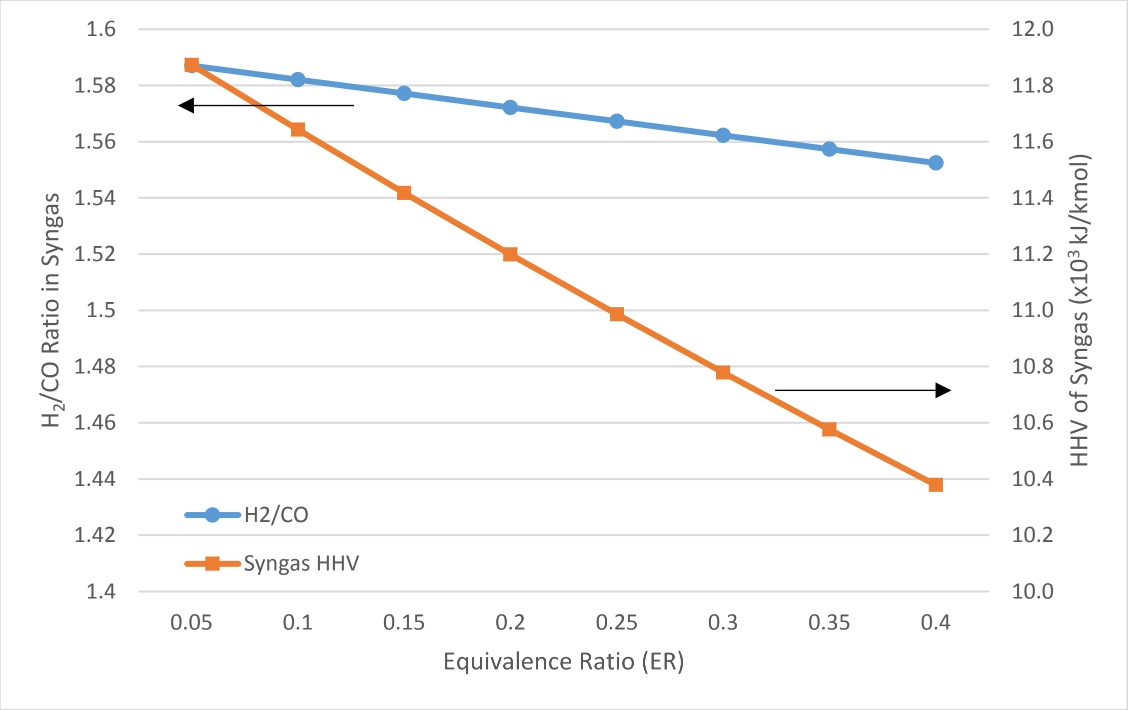

Figure 4-2: HHV and H_2/CO ratio of syngas from co-gasification with the variation of ER.

4.2 Effect of Temperature

In ASPEN HYSYS, all gasification reactions are modelled as an equilibrium reaction by either using equilibrium data or Gibbs free energy minimisation method, except oxidation reactions of carbon which is modelled as conversion reaction. Figure 4-3 shows the composition of syngas in exit gas composition for a temperature range of 700°C to 1200°C in entrained flow gasifier. This temperature range is in conjunction with the typical entrained flow gasification temperature.

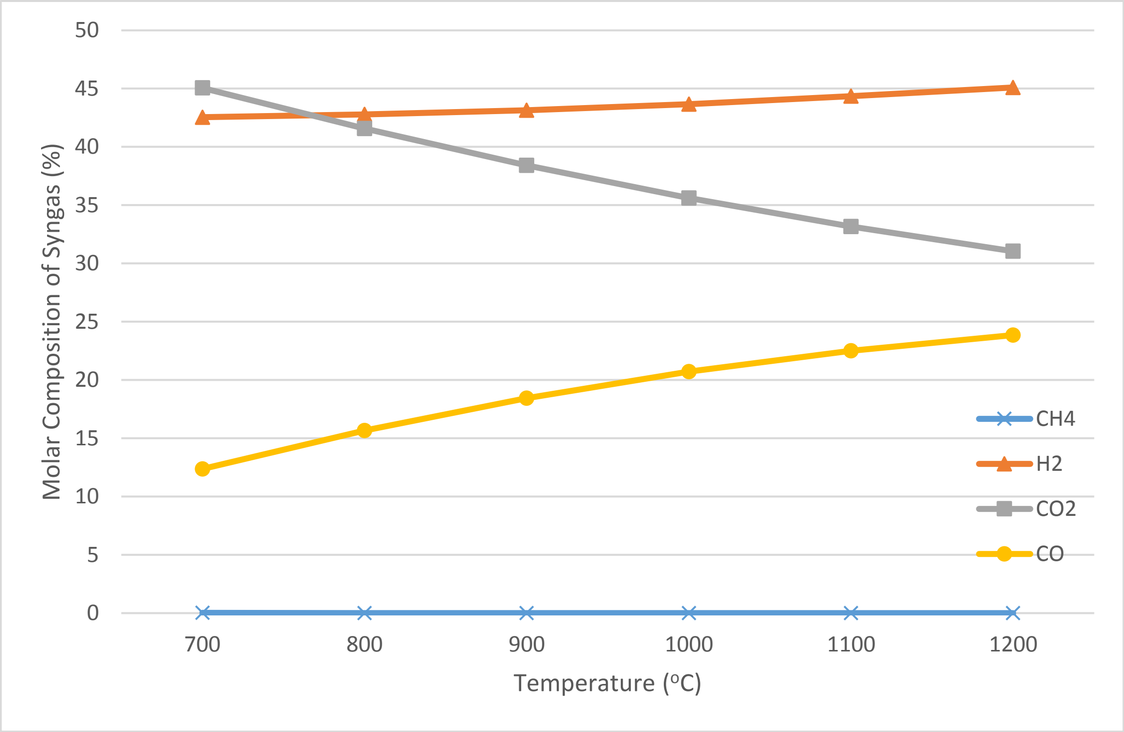

Figure 4-3: Variation of syngas composition with change in gasifier temperature at S/B: 1.5, B/C ratio: 1 and at ER = 0.3.

According to Bassyouni et al. (2014), water gas reaction (Eqn. 2.3) is the fundamental reaction giving rise to H_2 in syngas and higher temperature favours the formation of H_2 due to its endothermic behaviour. As H_2 is among the reactants in the hydrogasification reaction, which is also known as methanation (Eqn. 2.5), higher temperature will shift the equilibrium to the left for this exothermic reaction, saving hydrogen from consumption. Water-gas shift reaction (WGS) (Eqn. 2.6) is also an exothermic reaction, where higher temperature favours the formation of CO instead of H_2. Hence, the overall effect is a net increase in H_2 composition at higher temperatures.

The core gasification reactions, which comprise of water gas reaction (Eqn. 2.3) and Boudouard (Eqn. 2.4) produce CO and their endothermic behaviour is in confluence with higher temperature. Hence, the amount of CO increases with the increase in temperature in the gasifiers. Although WGS reaction (Eqn. 2.6) produces H_2 at the expense of CO., this reaction shifts the equilibrium backwards at higher temperature, which will save CO from consumption. Hence, the overall effect of Eqn. 2.3, Eqn. 2.4 and Eqn. 2.6 is a net increase in the CO concentration at higher temperatures. In addition, increasing temperature does not favour the formation of CH_4 and CO_2 in syngas. as a result, the amount of CH_4 and CO_2 in syngas appear to reduce consistently as temperature increases (Bassyouni et al., 2014).

The production of methane appears to be negligible in the simulation result, which is most probably due to the assumptions made in comparing result with literature. The assumptions can cause deviation in the composition of syngas in acceptable range. The concentration of CH_4 is also found very low for wood, coffee bean husks and green waste (Begum et al., 2013). Hence, the extremely low amount of CH_4 of syngas in this simulation work is justifiable.

Figure 4-4 shows the HHV of syngas and its H_2/CO ratio within the temperature range 700°C TO 1200°C. The H_2/CO ratio drops with the increase of temperature. Both H_2 and CO increase with the increase of temperature. However, the increment of CO is higher as Eqn. 2.3 and Eqn. 2.4 are endothermic reaction which favoured by the increase of temperature. The HHV increases as the temperature increases because concentration of CO and H_2 gases increase (Wang et al., 2008).

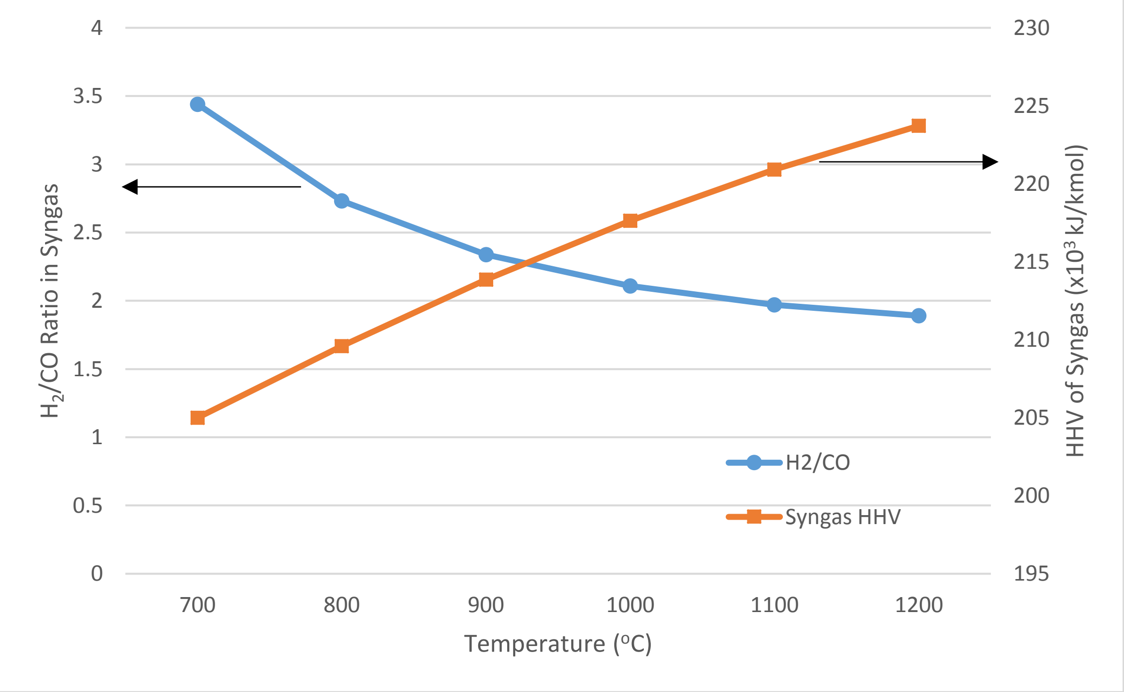

Figure 4-4: HHV and H_2/CO ratio of syngas from co-gasification with the variation of temperature in the range of 700°C – 1200°C.

4.3 Effect of Steam-to-Biomass Ratio

The effect of increase in steam-to-biomass (S/B) ratio is studied in entrained flow gasifier using ASPEN HYSYS and the simulation result is analysed. The results are shown in Figure 4-5. Saturated steam at 101.3kPa is used and S/B ratio is varied from 0.5 to 2 using a SET operation in the simulation for both biomass and coal gasification.

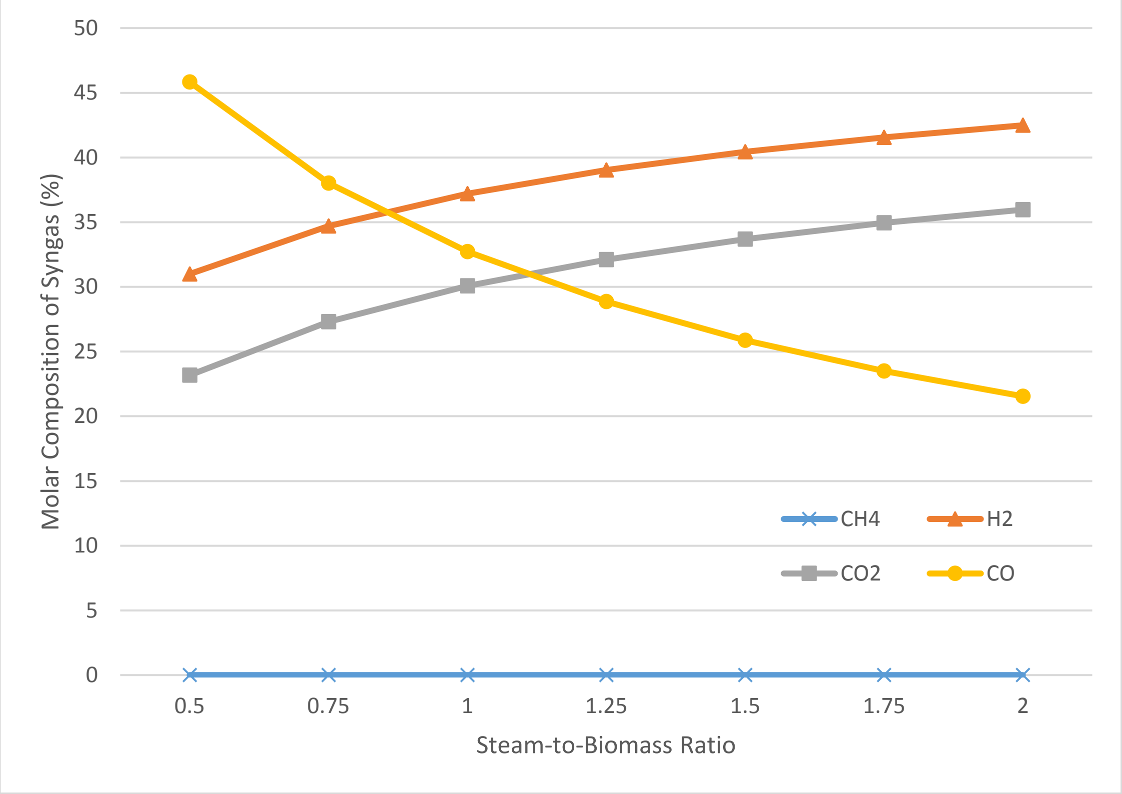

Figure 4-5: Effect of S/B ratio on syngas molar composition in the Cogasif-syngas stream (T: 1200°C, B/C: 1, ER: 0.3).

The function of injecting steam into the gasifier is to increase the heating value of the resulting gas as the CH_4 and H_2 contents increase (Bassyouni et al., 2014). The introduced steam shifts equilibrium right in water gas reaction (Eqn. 2.3) making CO and H_2. CO will further drive the equilibrium forward in WGS reaction (Eqn. 2.6). This behaviour will result in higher concentration of H_2 and CO_2. This shift will increase the concentration of methane in the hydrogasification reaction (Eqn. 2.5). The overall effect of introducing steam consists of increased concentration of H_2 and CO_2 as shown in Figure 4-5, which increases the heating value of syngas (Bassyouni et al., 2014).

Figure 4-6 shows the influence of S/B ratio on syngas HHV and H_2/CO ratio. The result shows a totally opposite trend from Figure 4-5. The H_2/CO ratio increases with the increase of temperature, while the HHV decreases as the temperature increases because of the increase of CO_2. As the temperature increases, CO_2 increases with the expense of CO due to WGS reaction (Begum et al., 2013). As steam inlet concentration increases, more water will be supplied and the unused water will contribute in lowering down the HHV of syngas. The rising H_2O content due to the increase of steam flow rate is the main cause for the decline in syngas HHV. CO and CH_4 are shifted and reformed respectively with the additional H_2O decreasing their contents and producing CO_2 (Doherty et al., 2009).

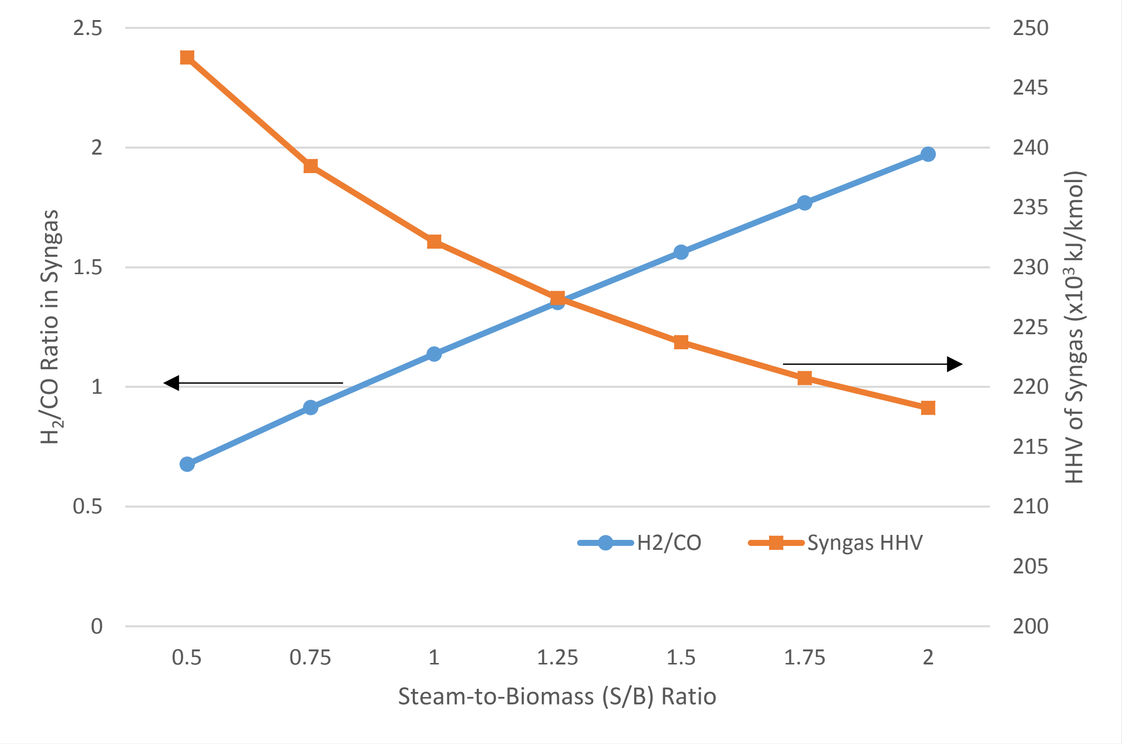

Figure 4-6: Influence of S/B ratio on the syngas HHV and H_2/CO ratio.

4.4 Effect of Biomass-to-Coal Ratio

In this co-gasification process simulation, the feedstock consists of two major components – biomass which is represented by raw EFB and Adaro coal. The effect of biomass-to-coal (B/C) ratio is studied, where B(0) stands for zero biomass component while B(100) means with biomass only as feedstock. The result of varying B/C ratio in gasification is stated in Figure 4-7.

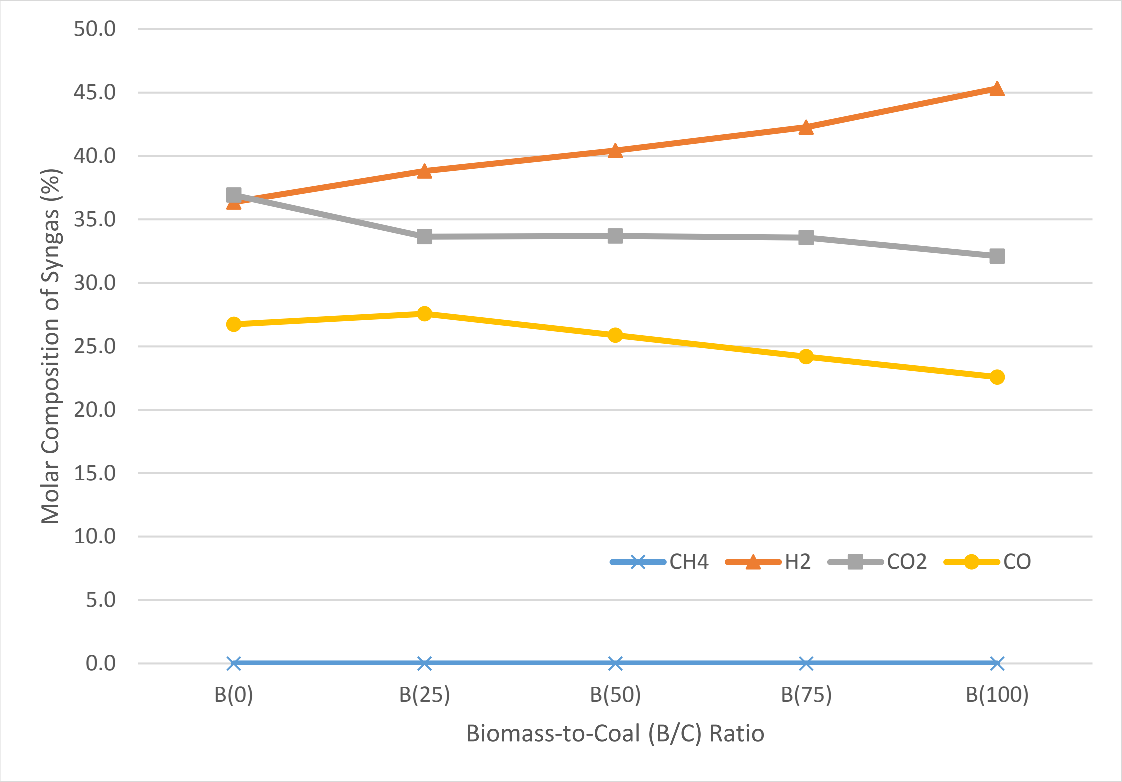

Figure 4-7: Effect of B/C ratio on syngas molar composition in the Cogasif-syngas stream (T: 1200°C, S/B ratio: 1.5 at saturated steam, ER: 0.3).

In co-gasification with varying B/C ratio, it is found that the percentage of CH_4, CO and CO_2 contents decrease with the increase of biomass. However, the percentage of H_2 increase as the biomass increase from B(0) to B(100). This result indicates that the biomass contains less fixed carbon compared to coal, hence the resulting gases contain more H_2 which is preferable as CO and CO_2 are greenhouse gases (Farzad et al., 2016). Greenhouse emissions, i.e. CO and CO_2, from plain coal gasification are higher than that from biomass gasification, most probably due to the high carbon content and low volatile percentage in coal (Brar et al., 2012). Figure 4-8 shows the influence of B/C ratio on the syngas HHV and H_2/CO ratio. It shows that both the H_2/CO ratio and HHV of syngas increases with the increase of biomass ratio. HHV of syngas of B(0) is found to be lower than that of B(100) because the carbon conversion in coal gasification part is lower compared to biomass gasification due to the retrofit design of co-gasification system.

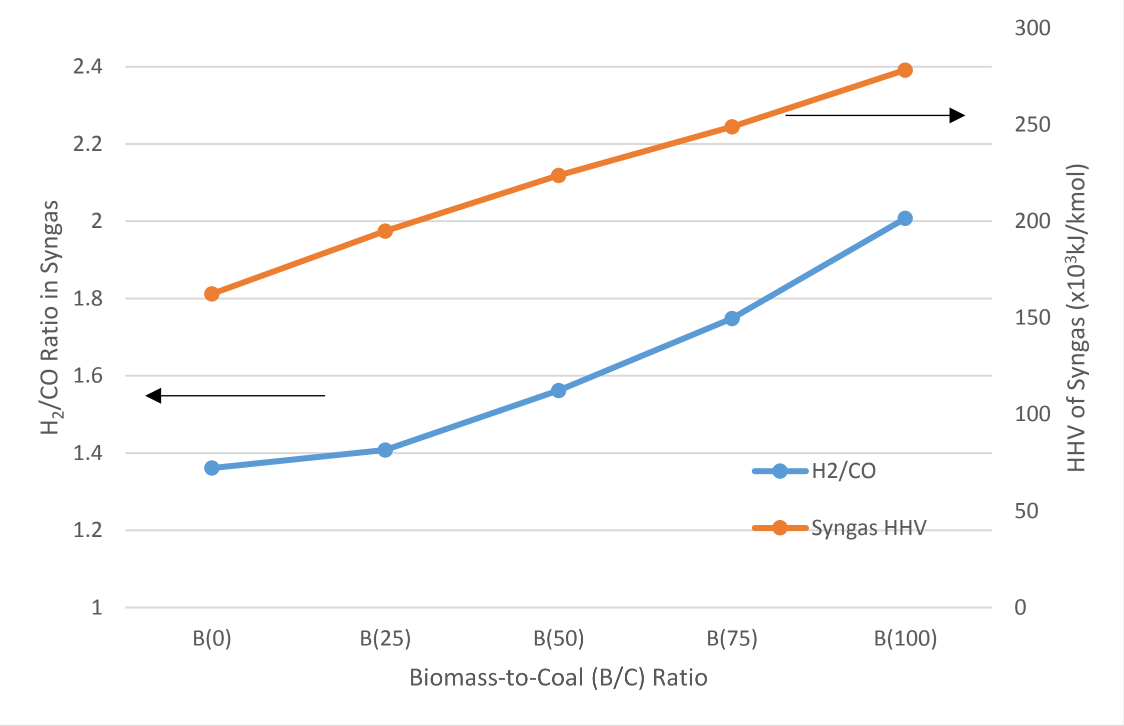

Figure 4-8: Influence of B/C ratio on the syngas HHV and H_2/CO ratio.

CHAPTER 5

CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

ASPEN HYSYS is used as the simulation software in setting up an equilibrium model for an entrained flow co-gasifier with feedstock of raw EFB as biomass and Adaro Coal as coal feed. The process is simulated at steady state to predict the synthesis gas composition with varying the parameters of ER, temperature, S/B ratio and B/C ratio. The model simulates the various zones accordance with the entrained flow gasifier. A process flow diagram (PFD) with various unit operations represents the simulation, which models EFB and Adaro Coal as hypothetical components. The feeds are then processed through a set of six equilibrium air steam gasification reactions to get syngas composition. The model is able to predict the performance of the gasifier and the simulation results are in fair agreement with the literature work with accepted adjustments based on reasonable assumptions. For a sensitivity analysis of the simulation, ER, gasifier temperature, S/B ratio and B/C ratio are varied and the results were analysed based on the literature works.

At higher ER, the performance of gasifier drops. It results in all the syngas components percentage drop in the product exiting stream of Gasifier-A. At higher temperatures, the performance of gasifier improves, as higher amount of H_2 and CO concentration in the syngas are produced. The increase of these two components will directly increase the heating value of the gas and cold gas efficiency. CO_2 concentration decreases while CH_4 remains almost consistent with increasing temperature. High S/B ratio improves the heating value of the syngas as it increases the concentration of hydrogen and methane with the expenses of CO. For B/C ratio parameter, the result shows that plain biomass gasification is not efficient as the amount of methane gas is not sufficient. With the mixture of coal, the syngas composition and amount are in good agreement. The increase of temperature, decrease of ER, decrease of S/B ratio, and increase of coal content in co-gasification will improve the HHV of syngas due to the high formation of useful syngas. H_2/CO ratio will reduce with the increase of ER, increase of temperature, decrease of S/B ratio and B/C ratio.

5.2 Recommendations

This research work can be further improved in terms of data accuracy, result analysis accuracy and simulation handling technique. There are a few recommendations which can be taken into consideration to improve the validity of this research work, as stated below.

1. Experiment work should be done in order to compare with and validate the process simulation result.
2. The accuracy of simulation data can be further improved by using kinetic methods in solving the simulation work. Kinetic information is essential to produce high accuracy of simulation work.
3. Take the elements such as moisture content, ash, tar formation and slag into account in simulating co-gasification is able to give more accurate and realistic result. However, the available data is limited.
4. Gasifier’s characteristic should be taken into consideration as well in simulating co-gasification.
5. Pre-treatment of feedstock and post-separation of syngas can be considered in giving a more completed process simulation of co-gasification.
6. Kinetic parameters of simulation can be obtained via experimental work to give a better result.

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